

P15058
C.C. HO 3366-11-P01508

American Journal of Science

JULY 1950 sec.

vol-248

THE ORIGIN OF THE PRE-CAMBRIAN BANDED IRON ORES

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ABSTRACT. The cause of banding in the Pre-Cambrian banded iron ores is sought in a cyclical deposition of colloids due to a periodic change in reaction (pH) of lake water. The two-component poor ores, with alternating bands of ferric iron oxides and silica, are the product of an acid-neutral semi-cycle; while the three-component poor ores, with alternating bands of the above two plus a third of iron silicates (often of iron carbonates), are the product of an acid-alkaline complete cycle. The correlation between these two types of ores seems to be one of a primary differentiation and not of a later oxidation of the latter into the former.

Both iron oxides and silica are the products of a mature weathering. The behavior of these components in solution is supposed to have been the same general trend as in the present soil profiles that have been generalized by the writer with his "ISOSIALS" in his recent paper (1944). In the genesis of bauxite deposits, the generalization upon chemical changes being based upon Sante Matson's experiments on the isoelectric points of soil colloids (1932).

In view of the regularity and purity of the bands as well as the vast thickness of the total iron ore beds, chemical weathering and deposition are known to have been preponderant and to have given rise to the most perfect "sedimentary differentiation" in the earth's history.

It is inferred that shallow lakes in a paralic basin and a monsoon-like climate were responsible for the unique environmental condition. That environment obtained only in the Middle Pre-Cambrian or only once in the history of the geologically cooling earth's surface, and its like has never been reproduced in later geologic ages.

PREFACE

DURING his service, from 1924 to 1945, in the Geological Department, South Manchuria Railway Co., the writer had the opportunity of visiting large and small deposits of iron ores in Manchuria, representing successive stages of metamorphism. In 1927, he visited the Mesabi and the Lake Superior Region, U. S., and in 1937, he visited the Rog deposits in the Ukraine, U.S.S.R.

During his service, with the writer as the geologist, he discovered a magnetic anomaly of over 6,000γ in a wide area

in the plain adjacent to the An-shan deposit, which was then prospected with deep borings over a period of years. The writer again visited the deposit and found three-compone ores at P'ai-chia-pu-tzu in which the original sedimentary structure was unusually well preserved.

Mr. G. Asano was then engaged in the studies on the banded iron ores and had published detailed studies in a series of papers, especially on lithologic characters of the ores. He pointed out that different deposits in Manchuria showed successive stages of progressive metamorphism, leading to the formation of eulysite.

The writer found that, if the Lake Superior and the Krivogorog be added to the top of the list, the series would become complete, because the bulk of the primary ore beds in the deposits consists in little-metamorphosed jaspilites.

The writer has made studies upon the mechanism of sedimentation and upon the progressive metamorphism. He has written a large paper upon the significance of the banded iron ores from the point of view of Pre-Cambrian historical geology. The present paper is a part of the larger paper, relating the genesis of the banded iron ores.

THE GENERAL PROPERTIES OF THE BANDED IRON ORES STRATIGRAPHY

The iron formations are found in the Pre-Cambrian rocks upon each continent, but not in all the Pre-Cambrian terranes. Their thickness is usually 100-200 m., the maximum being 450 m. in the Lake Superior region. In the latter region, they are found at three horizons in the Keewatin and the Huronian Systems. Although their age is considered to be Archean in Fennoscandia and India and in the Keewatin in North America, they are usually found among intermediate members between the most highly and the least metamorphosed rocks of the Precambrian: *e.g.*, in the Wu-t'ai (Liao-ho) System in Manchuria and North China, Saksagan System in Ukraine, Kalevian in Fennoscandia, and Huronian in North America.

There are iron ore beds in formations of the Wabana, Clinton and Oriskany in North America, Europe, Oolitic in England, etc. But the different type, lacking in siliceous bands,

when compared with those of the Pre-Cambrian. The banded iron ores are characteristic of the Pre-Cambrian, and in no later geologic ages were similar iron ore beds formed.

Where the iron deposits have been highly metamorphosed, their stratigraphic position can be determined only with great difficulty, but where the stratigraphic position is clear they are found, all over the world, in Proterozoic rocks. Moreover, it is striking that, within the Proterozoic cycles of quartzite, slate and calcareous formations, they are always associated with the clay-slate.

THE ORES, THEIR BANDED STRUCTURE AND THE GRAIN SIZE
OF COMPONENT MINERALS

The banded iron ores in Manchuria and other regions can be classified as follows:

TABLE 1

The Classification of the Banded Iron Ores

Banded iron ores	Poor ores	Hematite-magnetite-quartz schist Class 1
		Hematite-magnetite-quartz schist or magnetite-quartz schist with siderite, chlorite, grunerite, cummingtonite, hornblende, pyroxene, garnet or olivine Class 2
	Rich ores	Sedimentary—Hematite-magnetite-quartz schist Class 3
		Hydrothermal—Magnetite or martite rock with chlorite and dolomite Class 4
		Weathering—Limonite, hematite and martite . Class 5

The bulk of the banded iron ores in Manchuria consist of the hematite-magnetite-quartz schist (Class 1) or the poor ores with alternating bands of iron oxide and silica which correspond to jaspilites of Lake Superior and Krivoy Rog, only recrystallized and with coarser grain. The rest of them consist of finer-banded poor ores with alternating bands of three components, i.e., iron oxide, silica and iron silicates (often iron carbonates). This second group occurs in An-shan in thick beds in locally restricted areas, e.g., in Yuen-chien-shan and Ta-ku-shan areas. Those poor ores which contain amphiboles, pyroxenes or olivines represent successively higher-metamorphosed members of the group (Class 2), becoming similar with a eulysite in Sweden at their extremity. They occur

The rich ores (Class 3) are found in local areas in Krivoy

Figure 1. Cyclic banding in the banded iron ore from P'ai-chia-pu-tzu, An-shan.

Rog and An-shan, but their mode of formation has not yet been determined. The big deposit in Brazil is thought to be of this class. The ores of Class 4 are found in Krivoy Rog and in Miao-erh-kou. The ores of Class 5 form vast deposits in Central India, Lake Superior and Krivoy Rog regions. From an economic standpoint the value of the banded iron ores throughout the world rests on the rich ores of Class 5.

TABLE 2
The Width of Bands and the Grain Size of Component Minerals

Ores	Width of bands (mm.)	Diameter of mineral grains (mm.)
Two-component poor ores	{ Finely banded 0.5-2 Coarsely banded 2-10	Iron-minerals 0.005-0.3
Three-component poor ores	{ Silica bands 0.2-3 Fe oxide bands 0.2-2 Chlorite bands 3-5.5	Quartz 0.05-0.5

The above diameters of mineral grains are those of ordinary

Cycles	No	Bands	mm	No	Q	Gr	Ca	Th	M	Remarks
Acid-alkaline complete-cycles	4	1	0.3	1				⊕	+	Th > M
	3	2	0.4	2	⊕	+		+	+	mainly Q
	4	3	1.8	3	+	⊕				Gr > Q
	3	4	0.3	4	⊕	+	+			mainly Q
	2	5	0.8	5	⊕				⊕	M = Q
	1	6	0.3	6	⊕	+				mainly Q
	4	7	1.0	7	+	⊕				Gr > Q
	3	8	0.3	8	⊕	+		+		mainly Q
	2	9	0.4	9	⊕	+				
	1	10	0.3	10	⊕				⊕	M = Q
Alkaline semi-cycles	4	11	0.8	11	⊕					mainly Q
	3	12	0.3	12	⊕				⊕	M = Q
	4	13	1.0	13	⊕			+		mainly Q
	3	14	0.8	14	⊕	+	⊕		+	Gr > Q
	4	15	2.0	15			⊕	⊕	⊕	mainly Q
	3	16	0.3	16	⊕	+	+	+	+	Banding w. Th + M + Ca + M
	4	17	2.0	17	⊕	+	+	+	+	mainly Q
	3	18	0.3-0.8	18	⊕		+	+		Banding w. Th + M + Ca + M

Figure 2. Banding and mineral components of grunerite-thuringite-magnetite schist at Yuen-chien-shan. Q, quartz; Gr, grunerite; Ca, siderite; Th, thuringite; M, magnetite; ⊕, main component, (Materials after G. Asano).

hematite-magnetite-quartz schist or cummingtonite-magnetite schist in An-shan district. Those in jaspilites in foreign deposits are much smaller, while those in metamorphosed ores are a little larger.

It is remarkable that such fine bands should be piled up in beds, showing regular cycles, and should attain thickness of tens or even hundreds of meters without any interrupting beds of other sediments.

Examples of bands and regular cycles of three-component poor ores, which are exceptionally well preserved in some ores in the An-shan deposit, are graphed in figures 1 and 2.

G. Asano recently published very detailed studies upon the An-shan deposit and stated his views on the banded structure as follows:

"At the time of deposition, they were deposited as thin bands

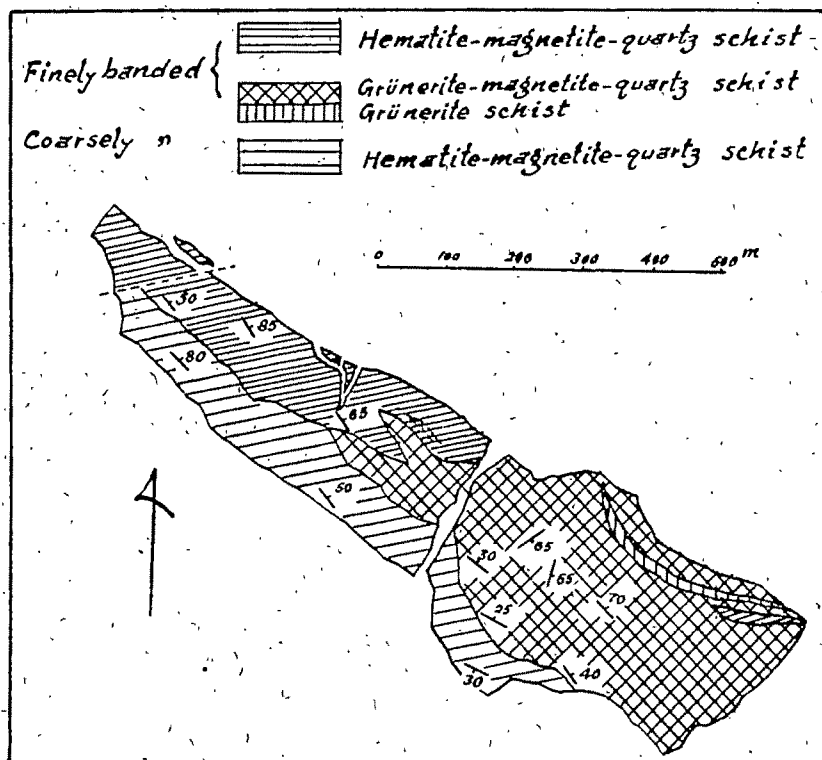


Figure 3. Ta-ku-shan ore body showing the distribution of different types of the banded iron ores (after G. Asano).

with different components and later partially oxidized and then subjected to regional or thermal metamorphism. According to their original constituents, they are either simply recrystallized or changed into certain suite of new minerals that are in equilibrium under new conditions. Since such suite become different from each other as the original constituents are different, they again result in different component minerals in each of the thin bands (Asano, 1941, p. 87)."

Asano further gives the following description regarding the mode of occurrence of three component ores with grunerite, cummingtonite, thuringite and siderite:

"Both at Yuen-chien-shan and Ta-ku-shan, ores with amphiboles occupy the whole thickness, from top to bottom, of the iron formation, but only in certain locally restricted areas among two component poor ores. When traced laterally in their prolongation, they entirely disappear from every horizon of the iron formation."

That is, the whole of a given iron ore bed may change from two-component into three-component ores according to locality and not to stratigraphic horizons (see fig. 8).

EARLIER VIEWS REGARDING GENESIS

Earlier views regarding genesis are summarized in the following table:

There seems to be a consensus of opinions as to the sedimentary origin of the poor ores. That they are formed by silicification of tuffs, as recently postulated by Dunn, is a unique view.

THE PROCESS OF SEDIMENTATION AND THE FORMATION OF THE BANDED STRUCTURE

POSITION OF THE IRON FORMATION IN THE PRE-CAMBRIAN CYCLE OF SEDIMENTATION

Deformation and progressive metamorphism of the Pre-Cambrian rocks containing the banded iron ores has in many places produced badly folded and contorted crystalline schists and gneisses, rendering determination of thickness as well as of the nature of the original sediments very difficult. However, in less metamorphosed areas, the iron formations are clearly interbedded with quartzite, clay-slate, limestone, etc., and not

TABLE 8
Earlier Views Regarding the Genesis of P
Banded Iron Ores

Genesis of poor ores.

		Raw materials	Transportation and deposition	Environm of deposit
Aqueous	Lake Superior	Weathering prod- ucts of volcanic rocks	Chemical deposi- tion	Sea botto
		Magmatic solution		
		Weathering prod- ucts of volcanic rocks	Transported as colloids protected by organic matter, Lake bot	deposited by bacteria
	An-shan	Weathering prod- ucts of Pre- Cambrian rocks	Transported as colloids protected by organic matter, Lake bot	deposited by electrolytes
		Weathering prod- ucts of basal metamorphics	Deposited by bacteria	Marsh
		Lateritic weath- ering products of Archaean gneiss	Transported as colloids protected by organic matter, Lake bot	deposited by electrolytes
sedimentation	Middle Sweden	"Volcanic solution"	Chemical precipitates	—
	Western Australia	Weathering prod- ucts on peneplain	Chemical precipitates	Peneplain
	Lake Superior	Volcanics	Ascending hot solution	—
	India	Banded tuffs	Hot spring	—

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<i>Genesis of rich ores</i>			
Genesis	Ore deposits	Ores	Authority
Weathering:— dissolution of SiO ₂ by descend- ing meteoric water	Lake Superior	Red hematite, limonite	Van Hise & Leith, 1941
	Singhbhum, India (float ore, blue dust)	Black hematite	Dunn, 1941
	Part of Krivoy Rog	Limonite	Svitalsky, 1937
Hydrothermal:— replacement by ascending hot solution	Lake Superior	Red hematite, limonite	Gruner, 1937
	Part of Krivoy Rog	Martite, magnetite	Svitalsky, 1937
	Miao-erh-kou	Magnetite	Tsurn, 1931
Sedimentation	Part of Krivoy Rog	Magnetite, hematite	Svitalsky, 1937
	Brazil	Magnetite, hematite	Leith & Harder, 1911

only accurate measurement of their thickness but also close observations upon their environments of deposition are possible.

In the Lake Superior area, the main iron formations (Biwabik and Ironwood) belong to the Middle Huronian, while there are other iron formations in the Upper and Lower Huronian. The Upper, Middle and Lower Huronian Systems each reaches nearly 1,000 m. in thickness. Each begins with a quartzite at its base, comprises thick clay-slate and marl or limestone in an ascending order; each shows a normal cycle of sedimentation. That is, normal cycles were repeated three times, each attaining a remarkable thickness. Besides, what is worth attention is that the iron formation in each case is associated with the clay-slate. The iron formations themselves reach thicknesses ranging from several meters to 450 m.

At Krivoy Rog, there is a quartzite at the base, next a thick phyllite, and above an alternation of phyllites, carbonaceous slates and limestones. The iron formation is associated with the phyllites. It occurs in a complicated synclinalorium, so that the measurement of thickness is difficult. According to Svitalsky (1937), however, the thickness is around 50 m. on an average, but near Ingulets Mine it reaches the tremendous figure of 1,500 m.

At Singhbhum in India, also, the newer Dharwar series, which contains the iron ore series, consists of sandstones and occasional conglomerate below and of shales above, the iron ore series being situated between the "Lower shales" and the "Upper shales" (Jones, 1984).

At An-shan, later granitic intrusions and overthrusts render the measurement of thickness difficult. Both hanging wall and footwall of the iron formation consist of intensely folded, gray, graphitic slate and phyllite. Those in the hanging wall are intercalated with beds of a black limestone. In those parts close to the contact with the iron ore beds, the cleavage of the slate and phyllite is usually parallel with the plane of contact with the ore, and consequently is apt to be mistaken for the bedding of the slate and phyllite. Therefore, the thickness of the latter is difficult to determine accurately but a reasonable assumption is over 900 m.

As stated above, the Pre-Cambrian systems show normal cycles of sedimentation and attain a remarkable thickness. Such large cycles as these are not always found in later geologic systems. This testifies that the Pre-Cambrian environments of sedimentation were unique.

THE MATURE WEATHERING

The fact that the iron formations in these cycles are always associated with clay-slates or phyllites, shows that the source of the materials of the ore beds may be found in the weathering and sedimentation in the particular environment under which the clay-slates or phyllites were produced, and that the views, long entertained in some quarters, that the iron was derived from submarine volcanoes or special volcanic rocks, are quite untenable. The ferruginous material should be reckoned as the product of mature weathering on a land surface. Indeed, iron oxide, free silica and aluminum hydroxide are three main products of mature weathering. Iron oxide and silica are constituents of all the banded iron ores, while the presence of aluminum hydroxide is not prevalent. According to Dunn (1941), however, frequent occurrence of kyanite and sillimanite deposits in the "Gondite series" of the Pre-Cambrian in India are derived from aluminous sediments, which in turn might have originated from ancient bauxites. According to

this view, the Pre-Cambrian of India contains all three main products of mature weathering.

According to recent observations by Woolnough in western Australia, there is widespread formation upon the surface of peneplaned regions of colloidal deposits, called by him "duricrusts," which have different chemical compositions according to the nature of the country rocks. Woolnough believes that the Pre-Cambrian banded iron ores were formed in the same way as these "duricrusts" upon a peneplain (1941).

Disregarding the presence or absence of all of the above three constituents at the same time, at least the development of such a large cycle and its regular repetition clearly point to constant physiographic and meteorologic conditions over a long period of time. Accordingly, after a period of deposition of a quartzite and like coarser materials, in the stage of deposition of finely divided suspensoid or colloid-like clay-slates, the land became low and flat, and chemical weathering became predominant over a long period of time. Under such an environment of weathering, silica in colloid form and partly in true solution, is removed from the weathering crust and accumulates in basins. The physiographic condition of the sedimentation of the Huronian System is believed to have been shallow seas or inland lakes and not open seas (Leith, 1934, pp. 157-158).

That the land surface was generally flat and lacking in steep topography is inferred from the long history of extensive weathering (being continued from the active primordial weathering in the Archean), and from the lack of coarser conglomeratic sediments comparable with those of the neo-Proterozoic and later systems. The movement of the earth's crust was perhaps epeirogenic rather than orogenic. T. Kobayashi, in his discussion on the sedimentational facies of the Sinian System in Manchuria and Korea believes that the tract as a whole had the nature of a kratogen (Kobayashi and Nakano, 1942).

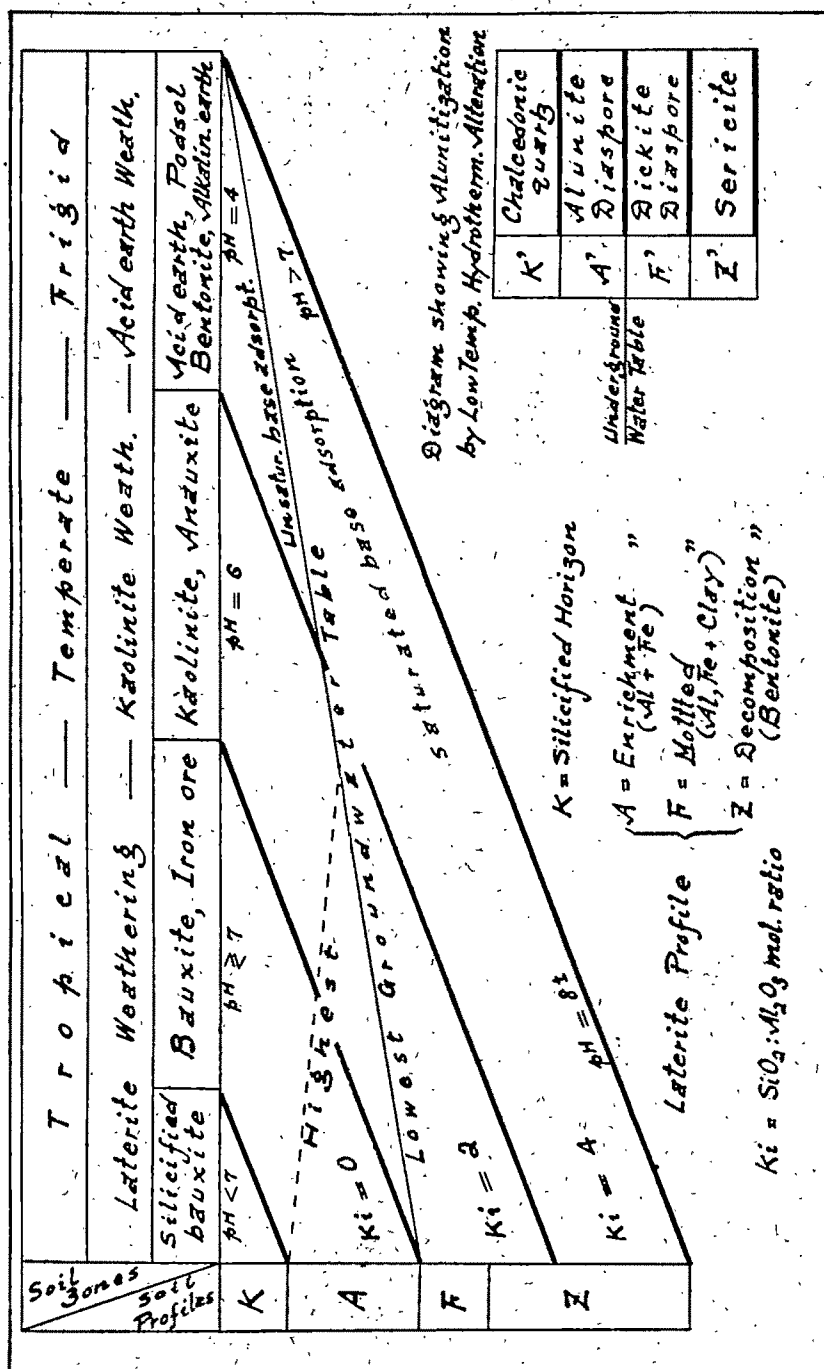
Iron migrates in acid environments and is precipitated in neutral and alkaline environments. Silica, on the contrary, migrates in alkaline and is precipitated in acid environments. That this holds in the zone of weathering has been quantitatively established by experiments on "isoelectric points" by Mattson (1932). The writer, in his former study

on the weathering and sedimentation of bauxites and banded-siltstone (aluminous shale), found that the distribution of soil colloids is in close connection with the acidity of the environment and that the results of Mattson's experiments are in good harmony with the distribution of soil colloids in the natural soil profile. The writer then found that the systematic distribution of soil colloids in a generalized soil profile of humid soils throughout the cold, temperate and tropical zones, could be shown graphically (fig. 4) by means of "equal silica-alumina molecular ratio lines, deeper in the soil profile toward the south, for which the writer proposed a new term "ISOSIALS" (Sakamoto, 1944).

What can be deduced with certainty from the generalized soil profile is that the soil solution above the water table, except in arid regions or seasons, is acidic, the acidity being highest in the cold zone in higher latitudes; whereas the solution below the water table, disregarding the climatic zones and seasons, is always alkaline (pH $8\pm$). Iron is dissolved by acid soil solution above the water table, resulting in a bleached soil, called a podsol, in regions of higher latitudes. Iron thus dissolved, upon reaching the water table below where the soil solution becomes neutralized, is precipitated as iron hydroxide, sulphide or phosphate and cements together fine particles of clay suspensoid, giving rise to the so-called "ortstein," or a compact and impervious hardpan. In humid seasons when soil solutions freely circulate and show a high acidity, part of the iron in true solution in the form of bicarbonate, etc., migrates to depressions and rivers and finally is precipitated in basins or on sea bottoms.

Silica is dissolved by alkaline water below the water table, the reaction being most manifest in the case of a laterite profile in the tropics. Rocks are deeply weathered, large quantities of alkalis are set free, mainly in the form of alkali carbonates, and the soil solutions become alkaline with pH around 8.

In this alkaline environment, replete with cations, clay colloids with the $\text{SiO}_2:\text{Al}_2\text{O}_3$ molecular ratio around 4 adsorb alkali and alkaline earth ions and form thick zones of bentonite. In upper horizons closer to the phreatic zone where soil solutions, more dilute with ions, migrate freely, those adsorbed cations are dissolved. Bentonites, becoming unstable, are easily desilicated and become clay colloids with a $\text{SiO}_2:\text{Al}_2\text{O}_3$ molecu-



lar ratio around 2, or a clay corresponding to a kaolinite. Still higher at the base of the phreatic zone, where horizontal flow of the underground water reaches its maximum, desilication is accelerated, finally setting iron and alumina free to form laterite. Where the underground water table fluctuates up and down in wet and dry seasons, as upon the surface of flat plateaus or low hillocks under a monsoon climate, lateritic iron ores and bauxite deposits are formed.

The process of laterization is thus desilication by alkaline underground water produced by the deep weathering characteristic of the tropical zone, with the formation of iron ores and bauxites as its end-product.

The iron ores and bauxites thus formed lose their iron when the environment becomes acidic, owing either to the coming back of a forest or to covering by peats. The bleached portion assumes a mesh appearance in plan and "schecken" or bands in vertical section. Also, in bauxite deposits, either the superficial portion, several decimeters thick, becomes bleached and silicified or the whole deposit becomes penetrated with light-colored kaolinite pipes with a funnel shape. This phenomenon may be taken as a retrogression of the iron and bauxite deposits.

In short, among the soil colloids, the most stable components remain and unstable components are dissolved out according to the acidity of the environment. Taking into account the above-stated facts, it is known that the iron in the acid environment above the water table and silica in the alkaline environment below the water table are both unstable and migrate until they reach an opposite environment where they are redeposited. Especially, in the profile above the water table in regions of higher latitudes, the environment is highly acidic, and iron (plus part of the alumina) is dissolved; whereas in the profile below the water table in the tropics the environment is highly alkaline, and silica is extensively dissolved and removed.

TRANSPORTATION AND DEPOSITION OF THE PRODUCTS OF WEATHERING

Taking these facts into consideration along with the inference above concerning Pre-Cambrian environmental conditions of weathering, a gleam of light seems to be thrown upon the

question of the accumulation of the unusually large quantities of iron and silica. The lack of coarse debris and the thick and normal cycles as in the Lake Superior area point to mature weathering as has already been pointed out by Prof. Leith (1934). Also, it is generally accepted that the Pre-Cambrian atmosphere was very rich in CO_2 gas. Under such physiographic conditions chemical weathering predominates, and, especially when the atmosphere contains much CO_2 , the surface water in contact with it can retain much bicarbonate in solution whose vapor pressure is in equilibrium with the large pressure of CO_2 in the atmosphere. In other words, rocks are rapidly decomposed, giving rise to deep weathering.

Supposing that the annual rainfall was great and divided into periodically wet and dry seasons, shallow grounds above the water table became neutral or even alkaline in a dry season and the phreatic zone near the water table became neutral or temporarily even acidic in a wet season. (This is the condition which obtains under the present tropical monsoon.) In wet seasons, iron migrated in the acidic surface water, while in dry seasons, silica migrated in the alkaline ground water. The iron and silica, though partly consumed in the formation of ferruginous "ortstein" or local silicification of country rocks, mostly went into solution and were transported into basins and depressions to be precipitated there as the sediments of "fernfällung."

Suppose further that these basins and depressions were wide but shallow, and were separated from the open sea with only low barriers. When there was much influx of surface water in wet seasons, the lake water easily overflowed into the sea; when the influx was stopped in dry seasons, the lake became an inland lake in an arid region. When the lake water became acidic in wet seasons, and cool water with free oxygen circulated down to the bottom by convection, then the whole lake water became acidic and oxidizing. In dry seasons, on the contrary, the influx of fresh oxygen-bearing and oxidizing water was stopped, and the lake water became neutralized owing to seepage of alkaline underground water. Owing to evaporation, the lake at last became an inland lake in an arid region in which the water stayed stagnant, oxygen was lost and, as the level of the lake water went down, its reaction became alkaline. In the next wet cycle, a fresh influx began and as

the level of the lake water arose, the reaction became neutral and finally, when it began to overflow, acid again.

Similar phenomena can be observed at present in rivers and lakes in the semi-arid region in north Manchuria. In the River Sungari, pH falls in flood seasons in summer, and rises in low water in winter. The water in many shallow lakes in the semi-arid steppe around Hailar, north Manchuria, is all weakly to strongly alkaline and none is acid.

In a lake where the reaction of water repeats regular cycles of acid-neutral-alkaline-neutral-acid, the conditions under which silica and iron are precipitated are inferred as follows: (The iron in the form either of colloids or of true solution is supplied to the lake in wet seasons. Ferrous iron is oxidized into ferric iron due to aeration. Then, in arid seasons, when the influx of surface water is stopped and the pH of the lake water gradually rises to neutral, ferric hydroxide is precipitated very rapidly, because its isoelectric point is pH 7. A little iron still remains in the solution. Due to the seepage of underground water and evaporation, the reaction becomes alkaline. Then silica is supplied to the basin in colloidal solution, gradually increasing its concentration as the evaporation goes on. Under an increased alkaline condition, colloidal silica and iron hydroxides combine with each other to form iron silicates (greenalite, chamosite, etc.), and the rise of temperature accelerates the precipitation of carbonates of iron and other compounds. Again, upon the return of a wet season and influx of fresh surface water, the reaction returns through neutral back to acid again. In this stage, silica is totally precipitated, and the lake water is acidic, contains free oxygen and receives a new supply of iron in solution. Thus the second cycle is started and repeated.)

FORMATION OF THE BANDED STRUCTURE

The relation between the periodic change of the reaction of the lake water and the supply and deposition of elements is shown schematically in figure 5.

The reaction of the water, beginning with acid (say pH $5\pm$) at A, passes neutral (pH 7) at N and reaches alkaline (say pH $9\pm$) at B; then returns through neutral at N' back to acid at A', completing the cycle. The supply and deposition

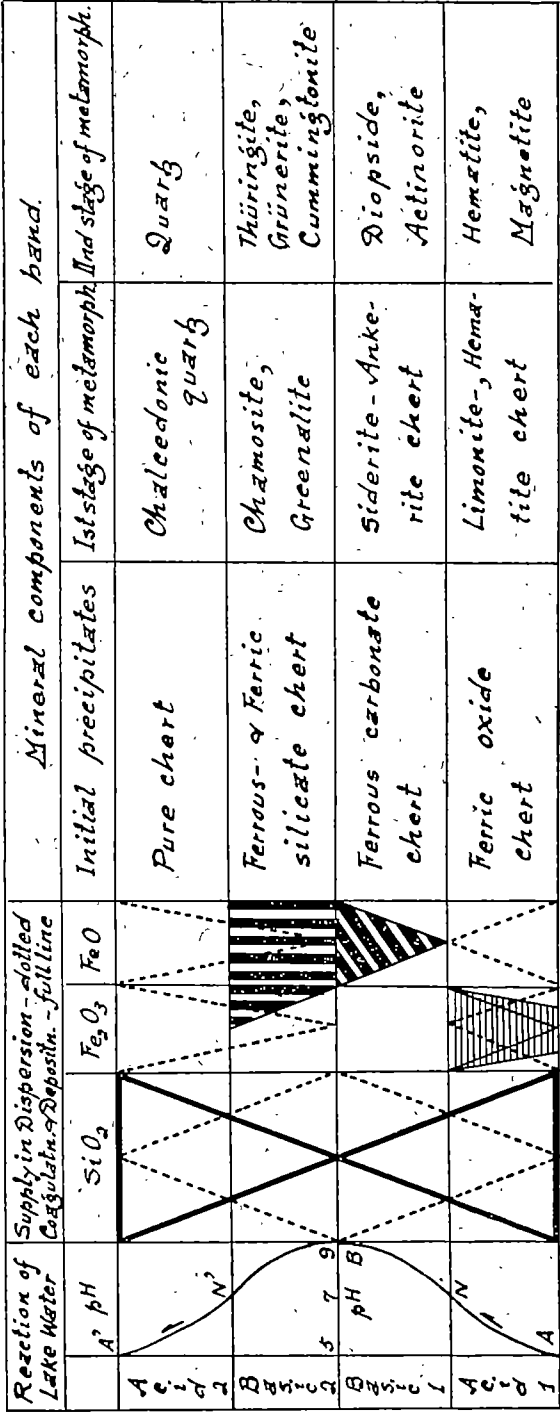


Figure 5. Supply and deposition of SiO₂, Fe₂O₃, and FeO in relation to reaction of lake water, resulting in regular banding with corresponding mineral components.

of each constituent are indicated by the areas cut, respectively, by the dotted and the full lines in the column of each constituent. The process in each of the four stages of one cycle is shown in the following table:

TABLE 4

The Sequence of Sedimentation Resulting in the
Formation of Banding

Reaction & Stage	Supply & deposition	Products (Bands)
Acid 1 A—N	SiO ₂ { Sup—gradually increases from minimum Dep—as chert, gradually decreases	Ferric oxide chert
	Fe ₂ O ₃ { Sup—decreases from maximum to minimum Dep—as limonite, concentrates in this stage, reaching maximum at N	
	FeO { Sup—decreases from maximum to minimum Dep—none	
Basic 1 N—B	SiO ₂ { Sup—increases to maximum Dep—as chert, decreases to minimum	Siderite chert
	Fe ₂ O ₃ { Sup—none Dep—none	
	FeO { Sup—none Dep—as siderite & greenalite begins and increases	
Basic 2 B—N'	SiO ₂ { Sup—decreases from maximum Dep—as iron silicates, gradually increases from minimum	Chamosite greenalite
	FeO & Fe ₂ O ₃ { Sup—begins Dep—as iron silicates, completed	
Acid 2 N'—A	SiO ₂ { Sup—decreases Dep—as chert, increases to maximum	Pure chert
	FeO & Fe ₂ O ₃ { Sup—increases to maximum Dep—none	

The concentration of electrolytes (dissociated ions of salts of alkalis and alkaline earths in the solution in the above cycle is at a minimum at A and a maximum at B. According to the experiments by Moore and Maynard (1929), "hydrosols of iron and silica stabilized by organic matter are preferentially precipitated by electrolytes with the same composition and concentration as in natural sea water. Iron is instantly pre-

precipitated while silica is precipitated much more slowly and incompletely."

As the concentration of electrolytes increases at the stage A-N in fig. 5, the deposition of ferric hydrosol is doubtless intensified; that of silica is partly deferred to the next stage N-B, where, being mixed with carbonates, it forms a siderite chert. The deposition of carbonate here is accelerated by the increase of temperature.

When the concentration of electrolytes reaches its maximum, ferric and ferrous iron combine not only with silica but also with Mg, Ca and Al, giving rise to new silicate minerals. Bauer in Africa has noticed that such laterite constituents as free silica and free alumina recombine to form a chlorite, resulting in a sort of silicification in alkaline inland lakes in the tropics. Moreover, such iron ore beds as the Wabana, the Minette and the Oolitic are characterized by chamosite as one of the main iron minerals. These iron ore beds were all deposited in sea water, and, hence, under a weakly alkaline condition. These facts bear witness to the formation of iron silicates of the chlorite family at the stage B-N'.

That silica is less sensitive to electrolytes than iron is also known by the experiments of Moore and Maynard. On the other hand it is very sensitive to change of acidity, as is very well known from observations of natural soil profiles.

Figure 6 shows a profile of a shallow lake upon whose bottom banded iron ores are being deposited. The supply and deposition of different constituents are schematically shown in the profile.

The level of the lake water is at its highest when the reaction is acidic (A), medium when neutral (N & N') and lowest when alkaline (B). The reaction of lake water and corresponding sediments and their areal distribution on the lake bottom are summarized as follows:

TABLE 5

Reaction of Lake Water and Corresponding Sediments		
Stage & reaction	Sediments (Bands)	Area of deposition
A — N (Acid 1)	Ferruginous chert	Entire lake bottom
N — B (Basic 1)	Siderite chert	Small area around center of lake
B — N' (Basic 2)	Chlorite	Small area around center of lake
N' — A' (Acid 2)	Pure chert	Entire lake bottom

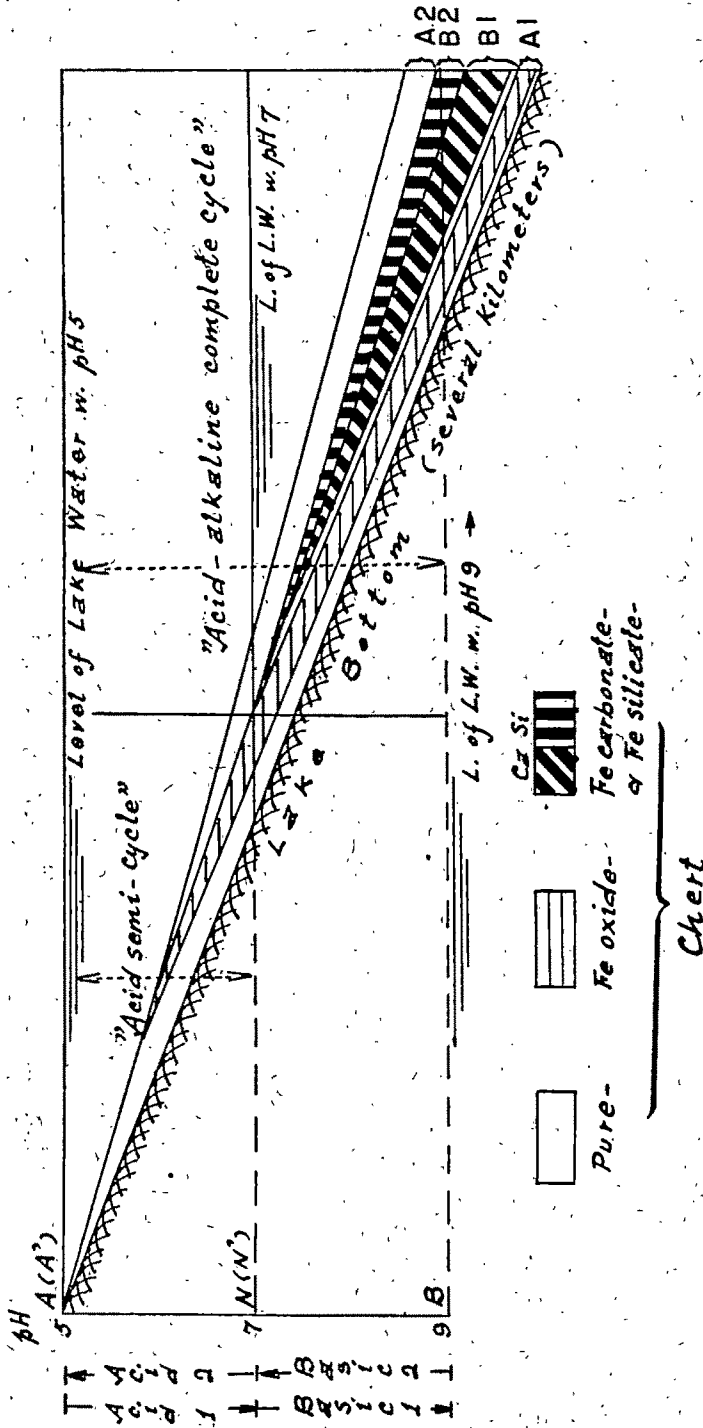


Figure-6. A diagrammatic cross section showing the deposition of SiO_2 , Fe_2O_3 , ferrous carbonate, and ferric silicates in relation to the reaction of (pH) and change of level of lake water. The deposit representing a cycle, A1 to A2, has total thickness of 15 mm.

In case of a complete cycle or a cycle with successive stages of acid-neutral-alkaline-neutral-acid as is seen in this figure, the sediments should be, from the bottom upward, a ferruginous chert, siderite and chlorite chert, and pure chert, thus giving rise to a distinct banding. Three-component poor ores are deposited in the deeper portion near the lake center; two-component poor ores in the shallow marginal portion.

In the case of an incomplete cycle or a cycle with successive stages only of acid-neutral-acid (a cycle which may be called an acid semi-cycle), two-component poor ores are deposited all over the lake bottom. In the case of an incomplete cycle of neutral-alkaline-neutral (a cycle which may be called an alkaline semi-cycle), three-component poor ores are deposited around the lake center.

The banded structure described in the foregoing pages, especially the one in the specimen collected by the writer at P'ai-chia-pu-tzu, An-shan (fig. 1), shows a remarkable coincidence with the banding in the acid-alkaline complete cycle in figure 6. Alkaline semi-cycles beside acid-alkaline complete cycles are shown in the banding of the ore from Yuen-chien-shan taken by Asano (fig. 2).

It has been stated above (and see fig. 3) that each of the two- and three-component poor ores has locally separate areas of distribution according to field observations. This peculiarity is easily explained by the scheme of deposition stated above.

The view that the two-component poor ores are secondarily derived from the three-component poor ores by oxidation seems to have been entertained almost universally. Yet, the observed distribution of those ores in which finely banded structure is extremely well preserved, like those in An-shan, clearly shows that it is more reasonable to assign this to primary sedimentation factors.

The two-component poor ores may, at a glance, seem to be entirely different from the three-component poor ores. Yet, upon closer observation, the latter ores are known to be the same as the two-component ores, only with another band of iron silicates or of iron carbonate cherts. This is naturally expected from the above-stated conditions of sedimentation. That is, an acid semi-cycle is included in an acid-alkaline complete cycle itself. In fact, the two-component ores of the lake margin of a complete cycle, traced laterally into the lake

center, pass into constituent bands of the three-component poor ores. Consequently it is quite impossible that such two-component ores are derived from three-component ores by a later oxidation. If the oxidation is a necessary procedure, it must have operated "exactly at the same time with the deposition of those thin bands, and that, with a regular intermittent recurrence." Such a syngenetic oxidation, if present, is only one of the sedimentational conditions of well aerated, hence oxidizing, lake water. Thus it coincides with the writer's "acid 1" or "acid 2" stages of sedimentation.

SUCCESSIVE CHANGES IN THE PRE-CAMBRIAN ENVIRONMENTS, AND THE GENESIS OF THE BANDED IRON ORES

The banded iron ores are distributed, on each continent, only in the Pre-Cambrian rocks and duplicates are not present in later geological systems. On each continent they constitute a great formation, the thickness sometimes reaching over 200 m. (Sedimentary iron ore beds in the Paleozoic and Mesozoic groups range from one to several meters thick at their maximum.

That the banded iron ores are the product of mature weathering has already been pointed out by Prof. C. K. Leith. According to the writer's study of the compositions and texture of the banded iron ores it is thought that they are products of an environment of distinct chemical weathering and sedimentation. Other sediments with which the banded iron ores are accompanied also point to the predominance of chemical changes.

Precipitates	Medium of deposition
Aluminous argillite	Acidic
Limestone & dolomite	Weakly alkaline
Chloritic argillite	Alkaline

These fine-grained, compact sediments attain a thickness of around 10,000 m. (17,000 m. at Ta-li-tzu-kou, east Manchuria), and sandy and conglomeratic rocks are of very rare occurrence. These facts point to large-scale chemical changes on one hand, and to very subordinate or negligible mechanical weathering and sedimentation on the other.

Thus, we must accept that such an extraordinary environment obtained only in the Pre-Cambrian era and has never been reproduced in later geologic ages. The Pre-Cambrian

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environments of deposition can be divided, at least, into three stages. The characteristic features of these three stages; the nature of original sediments and their metamorphic derivatives may be summarized as follows:

Stage	Environment	Original sediments	Metamorphic derivatives
I.	High temperature hydrothermal (alkaline chemical weathering)	Alkali-bentonite	Gneisses with subordinate schists
II.	Low temperature hydrothermal—cold water (alkaline & acid chemical weathering with subordinate mechanical weathering)	Aluminous argillite, limestone & dolomite, chert, iron hydroxide, iron silicate (chlorite)	Phyllite, mica, schist, chlorite schist, hornblende schist, banded iron ores, ferruginous chert, crystalline limestone, dolomite (magnesite), culysite, migmatite
III.	Cold water (same as Paleozoic & later) (predominating mechanical weathering)	Sandstone with aeolian rounded desert sands & dretkanter, shale, cherty limestone, glacial tillites	Quartzite, phyllite, cherty limestone, tillite

The sequence of the change of environments is supposed to have been the following:

1st stage:—Water vapor began to condense into hot rain which reached the earth's surface and began to act upon the lithosphere. In the atmosphere were still very large quantities of water vapor and CO₂, HCl and N₂. Consequently the density of the atmosphere was very large and, acting as the so-called heat blanket, it hindered the radiation of the earth's heat as well as that from the sun. As the result of the action of such a high temperature water upon the lithosphere, bentonites or active clays of the montmorillonite family were produced not only from tuffs and lavas but also from every kind of plutonic rocks.

Owing to very rapid decomposition of these igneous rocks, a large quantity of alkalis was set free and the earth's surface was strikingly alkaline. Consequently the bentonites adsorbed much alkali to become alkali-bentonites which showed nearly the same compositions as the parent igneous rocks, i.e., the stage is characterized "sedimentary non-differentiation."

2nd stage:—As the temperature gradually decreased, the speed of the rock decomposition slackened and consequently the amount of free alkali was decreased and owing to the presence of hydrochloric, carbonic and, probably, sulphuric acids, regional acidic environments were introduced for the first time upon the earth's surface, and a small amount of mechanical debris began to be produced.

As the acidic environment was introduced, the bentonites were leached of their alkalies, alkaline earths and later iron oxide, the remnants being changed into aluminous argillite. The soluble salts, either in a true solution or in a colloidal solution, were transported and deposited as chemical sediments.

Thus, at this stage chemical sediments gave rise for the first time to a vast amount of extremely well sorted sedimentary rocks on the earth's surface. The separation of easily soluble from difficultly soluble substances had been carried to its full extent in these rocks, *i.e.*, this stage is characterized by the highest degree of "sedimentary differentiation."

3rd stage:—Dry deserts and cold glaciers made their appearance upon the earth's surface and the environment took on features very close to those of the Paleozoic and later. Consequently mechanical sediments began to predominate.

Thus, in summarizing the characteristics of the original sediments in the Pre-Cambrian era, we can state that at the first stage there appeared non-differentiated clayey products still retaining the compositions of parent igneous rocks; then at the second stage there appeared very well differentiated typical sedimentary rocks of chemical deposits; and lastly at the third stage there appeared the alternation of a large amount of mechanical sediments and minor amounts of chemical deposits such as may be found in the Paleozoic and later ages.

The second stage represents a very long period of time during which the earth's crust, from a low temperature hydrothermal stage, cooled down to a stage similar to the Paleozoic and later ages. Its time duration is thought to be much longer than that of the first and the third stages. The banded iron ores are the product of the predominant chemical weathering and deposition under such a particular environment which obtained only once in the history of the earth's surface, toward the middle of the Pre-Cambrian era.

ACKNOWLEDGMENTS

Since 1940, Mr. G. Asano has published his studies in a series of papers which as a whole makes a comprehensive monograph. His petrographical studies on the banded iron ores in Manchuria are in more detail than any of those of earlier students and, above all, his description of the eulysitic ores and his hints at the progressive metamorphism of the ores are new and instructive.

The writer owes his idea of "ISOSIALS" of the generalized soil profile to the experiments on the isoelectric points of soil colloids by Dr. Sante Mattson of the Agricultural Experiment Station, New Jersey, U.S.A., and to the chemical analyses of clay minerals systematically taken from over 50 meters of a typical lateritic profile at Bintan Island, Netherland East Indies, by Dr. van Bemmelen of the Geological Survey, Bandoeng, Java.

To Prof. C. K. Leith and Prof. W. H. Twenhofel, the writer is indebted for his interest in the Pre-Cambrian and in sedimentation, since 1927-28 when the writer was a student in the Graduate School at the University of Wisconsin. Their addresses and writings have been an inspiration to the writer ever since, and he wishes to express his sincere gratitude to these gentlemen and to his other former professors. To Prof. Twenhofel special thanks are due for giving generously of his time in critical reading of the manuscript.

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THERMAL STUDY OF JAROSITE

J. LAURENCE KULP AND HANS H. ADLER

ABSTRACT. Jarosite, argentojarosite, and plumbojarosite are examined by differential thermal analysis and X-ray diffraction. The structural and chemical changes which these minerals undergo on heating are discussed and compared with alunite.

In general two endothermic peaks at about 400° C. and 700° C. are the major thermal features. The first large endothermic peak is associated with the OH loss and the jarosite structure destruction. This is followed by a small exothermic peak attributed to crystallization of Fe_2O_3 (hematite). The second endothermic peak is due to decomposition of $\text{Fe}_2(\text{SO}_4)_3$ produced during the jarosite lattice destruction. A number of thermal curves of jarosite group minerals from typical localities are discussed. Substitution is considered from a standpoint of mineral structure and geochemical conditions.

INTRODUCTION

IN recent years application of differential thermal analysis to the solution of mineralogical problems has met with considerable success.

The types of equipment, theory, and use of differential thermal analysis have been reviewed by Speil, Berkelhamer, Pask and Davies (1945), Grim and Rowland (1942), and Kerr and Kulp (1948). The method is applicable to minerals which undergo endothermic or exothermic changes within the limits of the temperature ranges ordinarily covered by available apparatus. Most work has been carried out from room temperature to about 1100°C. but at times higher temperatures have also yielded valuable information.

Although the thermal curves for alunite and jarosite have previously been published, much remains to be said concerning the thermal history, the variations in the thermal curves within the alunite-jarosite group, and the correlation of these phenomena with structure. It is the purpose of this investigation to indicate the typical thermal curve for a number of jarosite minerals, to describe the chemical reactions which produce the characteristic peaks in the thermal curve, and to examine the possible cation substitution.

The minerals of the jarosite group are:

Jarosite	$\text{K}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$
Argentojarosite	$\text{Ag}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$
Plumbojarosite	$\text{PbFe}_6(\text{OH})_{12}(\text{SO}_4)_4$
Ammoniojarosite	$(\text{NH}_4)_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$
Natrojarosite	$\text{Na}_2\text{Fe}_6(\text{OH})_{12}(\text{SO}_4)_4$

Because of the frequency of occurrence, relative economic importance and availability of specimens, the potassium, silver and lead members were studied.

ACKNOWLEDGMENTS

The authors wish to acknowledge the scientific counsel of Professor Paul F. Kerr. They are also indebted to Professor Ralph J. Holmes for many useful suggestions in X-ray diffraction technique.

TECHNIQUES AND PROCEDURE

X-ray diffraction was used to confirm the identity of the samples and to determine the structural changes of the material on heating. Debye powder photographs were taken with iron radiation. The various members of the jarosite group give sufficiently different powder patterns to permit rapid identification.

All specimens were subjected to semi-quantitative chemical analysis using the Curtman (1942) scheme. In table 1 the cations are recorded as major, minor, or trace constituents. Through analysis of samples with known metallic content it is estimated that "major" refers to greater than 5%, "minor" indicates 1-5% and "trace" considerably less than 1%.

The multiple differential thermal analysis apparatus employed is described by Kerr and Kulp (1948). A heating rate of 12.5° per minute up to 1000°C. was used. The material was ground to pass 300 mesh, packed uniformly in the thermocouple well, and heated without covering. This small particle size was found necessary to obtain comparable curves, for, although some of the specimens are reasonably coarse, others are extremely fine powders.

SPECIMEN DESCRIPTION

The specimens studied were obtained from the Egleston Mineral collection of the Department of Geology, Columbia University. In addition, a synthetic jarosite prepared by Professor Paul F. Kerr after the method of Fairchild (1933) for an earlier investigation was available.

The members of the jarosite group show few distinguishing features in hand specimen. All occur as soft masses or aggregates of fine pale-yellow to dark-brown flakes varying in luster.

Optical examination indicated the absence of impurities aside from a small quantity of an opaque red substance found associated with jarosite from several localities. X-ray examination and chemical tests showed it to be quartz coated by goethite. The optical properties of the specimens studied fell within the range recorded in the literature.

In each case the material for thermal analysis was carefully selected for homogeneity.

"Argentojarosite" from Eureka, Utah, "plumbojarosite" from Almada, Mexico, and "plumbojarosite" from Pioche, Nevada, are each composed of both yellow and brown material. X-ray examination indicates the brown material from Almada to be predominantly plumbojarosite, whereas the yellow portion is apparently an intergrowth of plumbo- and argentojarosite. To verify this a 1:1 mixture of argentojarosite from Eureka, Utah, and plumbojarosite from the Eryscian mine, Chihuahua, Mexico, was artificially prepared and an X-ray diffraction powder pattern taken. The pattern obtained was identical to that of the yellow material from Almada, Mexico.

THERMAL HISTORY AND STRUCTURE

The thermal curves of the specimens studied are shown in figure 1. All are characterized by two major endothermic peaks. These are supplemented or modified by the particular chemical constitution of the mineral lattice, intergrown members of the group, and active or inactive impurities.

In order to gain a better understanding of the structural and chemical behavior of these minerals on heating and thereby to interpret the thermal curves adequately, the most typical specimens of jarosite, plumbojarosite and argentojarosite, were heated just past each significant peak, then examined by X-ray methods. For these experiments the following specimens were used: jarosite, Santa Maria mine, Jelardena, Durango, Mexico; plumbojarosite, Eryscian mine, Chihuahua, Mexico; and argentojarosite, Tintic Standard mine, Eureka, Utah.

The thermal decomposition of alunite has already been studied by Fink, Van Horn and Pazour (1931). Since the structures of alunite, $K_2Al_6(OH)_{12}(SO_4)_4$ and jarosite, $K_2Fe_6(OH)_{12}(SO_4)_4$, are similar (Hendricks, 1937), an understanding of the thermal decomposition of alunite facilitates experimentation within the jarosite group. The aluminum or iron

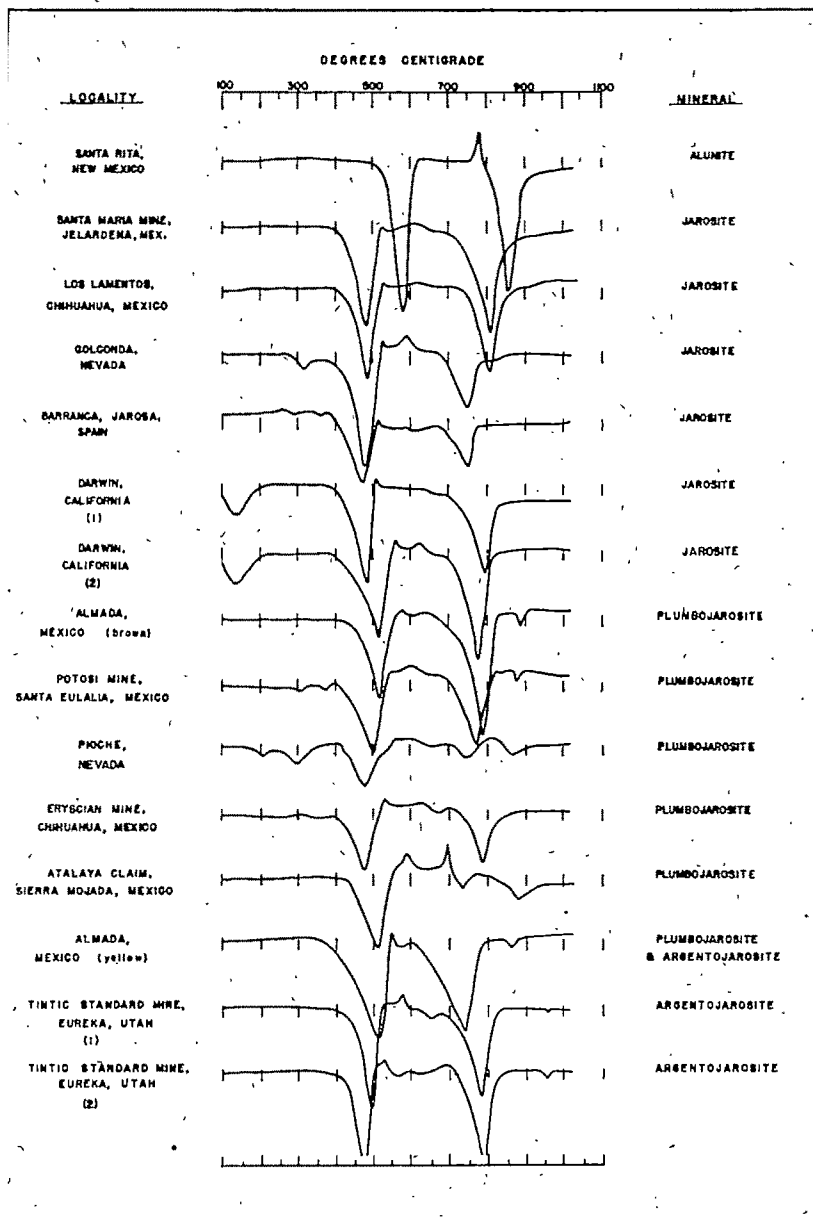


Figure 1. Differential thermal curves of alunite and jarosite specimens.

is surrounded octahedrally by four hydroxyl groups and two oxygen atoms of sulfate groups. Potassium has a coordination number of twelve, and is surrounded by oxygen and hydroxyl groups. The linkage is such that a loss of OH would cause complete decomposition of the structure, and then considerable rearrangement must take place in order to form hematite, ferric sulfate, or other possible residual products.

Fink, Van Horn and Pazour (1931) heated alunite for long periods at various constant temperatures and studied the products by means of X-ray diffraction. Alunite heated 18 to 48 hours from 250° C. to 500° C. gave only sharp lines characteristic of the mineral. Heating for 20 hours at 600° C. produced a diffuse pattern indicating a small amount of $K_2SO_4 \cdot Al_2(SO_4)_3$, while heating for 18 hours at 700° C. gave sharp lines of the potassium aluminum sulfate. At 800° C. alpha- Al_2O_3 lines became evident as did some K_2SO_4 lines, but the potassium aluminum sulfate lines were absent. Heating further to 1000° C. and 1200° C. only sharpened the alpha- Al_2O_3 and K_2SO_4 lines.

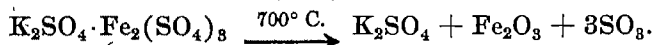
The thermal curve of the alunite from Santa Rita, New Mexico (fig. 1) can be readily interpreted in terms of the chemical changes. It should be noted, however, that the dynamic differential heating method produces peaks at somewhat higher temperature than the static equilibrium method used by Fink *et al.* (1931).

The first large endothermic peak occurs at the point of destruction of the alunite lattice according to the equation $K_2[Al_3(SO_4)_2(OH)_6]_2 \xrightarrow{550^\circ C.} K_2SO_4 \cdot Al_2(SO_4)_3 + 2Al_2O_3 + 6H_2O$. The X-ray pattern at 600° C. is diffuse but the faint lines of the alum salt, $K_2SO_4 \cdot Al_2(SO_4)_3$, are discernible. That amorphous alumina is present at this stage is confirmed by the fact that the solution velocity in strong alkali of the mass heated to 600° C. is greater than that of alunite heated to any higher or lower temperature and results in practically complete recovery of alumina. As the temperature is increased to 700° C. the alum crystallization continues and gives sharper X-ray lines while the alumina remains in the amorphous state. The differential thermal curve reveals that the exothermic alpha- Al_2O_3 recrystallization is abrupt and immediately precedes the decomposition, $K_2SO_4 \cdot Al_2(SO_4)_3 \rightarrow K_2SO_4 + Al_2O_3 + 3SO_3$.

Above the second large endothermic peak there is little

change in the structure, but crystal growth continues with increasing temperature. Presumably the heat effect of the crystallization of the Al_2O_3 produced as a result of the decomposition of the alum salt at 800°C . is incorporated into the general endothermic peak.

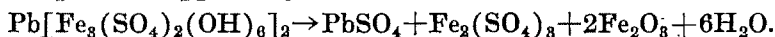
The thermal history of jarosite from the Santa Maria mine is similar but not strictly analogous to that of alunite. While the structure of the two minerals is essentially the same, the chemical reactions that ensue upon heating are different. The destruction of the lattice occurs about 100°C . lower in jarosite than in alunite. This is probably due to the OH-Fe bond being weaker than the OH-Al bond, which behavior is suggested by the large ionic radius of Fe^{+3} ($0.67\text{\AA}$) as compared to Al^{+3} ($0.57\text{\AA}$). The decomposition reaction is similar to that of alunite, *i.e.*, $\text{K}_2[\text{Fe}_3(\text{SO}_4)_2(\text{OH})_6]_2 \xrightarrow{460^\circ\text{C.}} \text{K}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3 + 2\text{Fe}_2\text{O}_3 + 6\text{H}_2\text{O}$ with one significant difference that, whereas the amorphous alumina does not recrystallize until about 780°C ., the Fe_2O_3 produced in this decomposition is crystallized directly after the destruction of the jarosite lattice. This is reflected by the small exothermic peak at about 500°C . immediately following the endothermic decomposition. While this small sharp exothermic peak is observable on the Santa Maria mine specimen, it is more clearly developed in most of the other curves. Material heated to the end of the endothermic reaction and cooled quickly gave a diffuse X-ray diffraction pattern indicating the presence of hematite and $\text{K}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3$. Heating the product of the initial decomposition at 500°C . for 17 hours produced sharper lines but otherwise left the pattern unchanged. K_2SO_4 and $\text{Fe}_2(\text{SO}_4)_3$ were intimately mixed in a 1:1 molecular ratio and heated at 580°C . for several hours. The pattern produced matched the non-hematite lines in the decomposed jarosite. Since the iron oxide had crystallized by 600°C ., no further reaction was observed prior to the second decomposition which appeared at about 700°C ., *i.e.*,



The X-ray diffraction pattern of material heated past the second endothermic peak showed only K_2SO_4 and hematite lines. That the endothermic reaction corresponding to the decomposition of $\text{K}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3$ occurs at lower tempera-

tures than that for the $K_2SO_4 \cdot Al_2(SO_4)_3$ in alunite, is also consistent with the structural picture.

A similar experimental procedure with plumbojarosite from the Eryscian mine yielded slightly different results. The decomposition apparently is as follows:

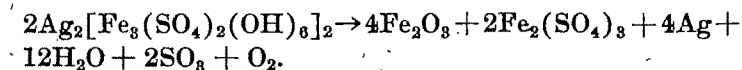


The material submitted to X-ray diffraction after the first endothermic peak produced $PbSO_4$ and $Fe_2(SO_4)_3$ lines with an indication of diffuse hematite lines.

The double-salt $PbSO_4 \cdot Fe_2(SO_4)_3$ probably does not form due to the difference in the structure of $PbSO_4$ (barite type) as compared with the K_2SO_4 type (Evans, 1939). The "holes" in the plumbojarosite structure resulting from divalent lead ions occupying only half of the possible potassium ion positions, probably are an additional hindrance to the double salt formation.

At higher temperatures (700° C.) the $Fe_2(SO_4)_3$ breaks down into hematite and sulfur trioxide leaving a residue of Fe_2O_3 and $PbSO_4$ at 1000° C., which was confirmed by X-ray diffraction examination.

The argentojarosite (Tintic Standard mine) apparently decomposes in still another way. Due to the instability of Ag_2SO_4 at the temperature of argentojarosite decomposition, the following reaction is postulated:



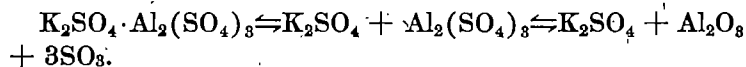
The loss of oxygen is expected as the decomposition temperature of Ag_2O is only 300° C. X-ray diffraction patterns of the material heated just past the first endothermic peak produced much more diffused lines than patterns taken after similar treatments to jarosite or plumbojarosite. Faint diffuse lines of hematite and $Fe_2(SO_4)_3$ were detected. No lines corresponding to Ag_2SO_4 were present. The absence of Ag_2SO_4 at 500° C. is indicated by two other facts. First, there is no other peak which would indicate the breakdown of Ag_2SO_4 up to its decomposition temperature at 652° C. Second, the corrosion of the nickel specimen holder is more intense than that observed after decomposing jarosite or plumbojarosite. This indicates the release of SO_3 in the presence of water vapor during the breakdown of the argentojarosite lattice.

Again at about 800° C. the $\text{Fe}_2(\text{SO}_4)_3$ decomposes into Fe_2O_3 and SO_3 . The high temperature product in this case is primarily hematite and some metallic silver. The presence of this metal is shown by the endothermic peak at about 950° C. The melting point of pure silver is 960.5° C. It was found that this peak was reversible and that with each successive melting it lost some of its amplitude. This would occur if the silver gradually distilled into cooler parts of the apparatus.

From this information it is to be expected that the ammonio- and natrojarosite thermal curves will show similar characteristics. The $(\text{NH}_4)_2\text{SO}_4$ produced in the ammoniojarosite decomposition should volatilize immediately, leaving again hematite and $\text{Fe}_2(\text{SO}_4)_3$. The ammoniojarosite curve should therefore resemble the argentojarosite curve minus the 950° C. endothermic dip.

The natrojarosite may more closely resemble potassium jarosite in its thermal history, Na_2SO_4 remaining at 1000° C. Whether a double salt $\text{Na}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3$ would form is questionable. While the Na_2SO_4 structure is more similar to that of K_2SO_4 than to PbSO_4 , it is nevertheless different and that difference may be enough to make the double salt formation energetically unfavorable.

Natroalunite would be expected to follow the alunite decomposition pattern closely except again for the possible absence of double salt formation. The double salt formation has relatively little effect on the thermal curve since it decomposes at only slightly higher temperatures than pure aluminum sulfate. This can be ascribed to the displacement of the equilibrium,



THERMAL ANALYSIS CURVES

The thermal curves of the specimens studied in the temperature range 100-1000° C. are shown in figure 1. Table 1 gives the summary of the critical chemical and X-ray data.

The curve of the Santa Rita, New Mexico alunite has been fully discussed in the foregoing section. The jarosite from the Santa Maria mine gives a thermal curve with no evidence of foreign constituents. Chemical analysis indicates a trace of lead which does not appear to affect the thermal curve to any appreciable extent. The high-purity jarosites show at least

TABLE 1

Locality	Mineral (based on X-ray data)	Chemical Data\				
		Pb	Ag	K	Al	Fe
Santa Maria mine, Jelardena, Mex.	Jarosite	trace	X	major	X	major
Los Lamentos, Chihuahua, Mex.	Jarosite	trace	X	major	X	major
Golconda,* Nevada	Jarosite	—	—	—	—	—
Barranca,* Jarosa, Spain	Jarosite	—	—	—	—	—
Darwin, (1) & (2) California	Jarosite	X	X	minor	—	major
Almada, (brown) Mexico	Plumbojarosite	major	trace	X	X	major
Potosi mine, Santa Eulalia, Mex.	Plumbojarosite	major	trace	X	X	major
Ploche, Nevada	Plumbojarosite	major	—	X	X	major
Eryscian mine, Chihuahua, Mex.	Plumbojarosite	major	X	X	X	major
Atalaya claim, Sierra Mojada, Mex.	Plumbojarosite	major	X	X	minor	major
Almada, (yellow) Mexico	Plumbojarosite and Argentojarosite	major	major	X	X	major
Eureka, (1) & (2) Utah	Argentojarosite	X	major	X	X	major

— not determined

X not detected

* These specimens were subjected to X-ray examination during the course of previous investigations undertaken by Professor Paul F. Kerr and were used in this study for comparison purposes only.

two significant differences to the plumbojarosites. First, the initial decomposition begins at a slightly lower temperature, *e.g.*, most of the jarosite specimens start decomposition from 370-400° C., while practically all of the plumbojarosite and argentojarosite specimens start decomposing about 400° C. and above. A second difference is found in the temperature of the second endothermic peak. Here the jarosite is consistently higher, ranging from 810-820° C., in the high-purity specimens. The Golconda and Barranca specimens contain appreci-

able impurities as shown by X-ray patterns and the small amplitude of the thermal peaks. Plumbo- and argentojarosite give this high temperature endothermic peak about 780-790° C. It can also be seen that the latter minerals tend to start this final $\text{Fe}_2(\text{SO}_4)_3$ decomposition at a lower temperature. The double salt formed during the decomposition of jarosite apparently increases the stability of the ferric sulfate.

The Los Lamentos jarosite is similar to the Santa Maria specimen discussed above.

The Golconda and Barranca specimens yield typical curves. The $\text{Fe}_2(\text{SO}_4)_3$ decomposition peaks, however, occur at somewhat lower temperatures due to the presence of impurities. The Golconda specimen shows the presence of goethite in the 240° C. endothermic peak and may contain siderite along with some inert impurity.

The Darwin jarosite is not homogeneous. A sericite-like material is present which may produce the slight lowering of the high temperature endothermic peak.

The Almada plumbojarosite (brown) shows the presence of a small endothermic peak at 885° C. indicating a small amount of admixed argentojarosite. The X-ray diffraction pattern shows several faint lines of argentojarosite. It appears impossible to entirely separate this brown material from the yellow in hand specimen. The yellow material apparently contains a high percentage of argentojarosite.

The Potosi mine plumbojarosite has considerable impurities associated with it. The endothermic dips prior to the main decomposition are due to goethite and possibly some sulfide. The 875° C. endothermic peak is attributed to the melting of silver derived from the decomposition of admixed argentojarosite. The X-ray pattern of the Potosi specimen confirms the presence of argentojarosite.

The Pioche specimen appears to have considerable inert impurity, thus lowering the amplitude of the peaks. Some evidence of a clay mineral of the montmorillonite group is suggested. The high temperature peak is lowered due to dilution and the 863° C. peak may be the decomposition of a small quantity of $\text{Al}_2(\text{SO}_4)_3$, either derived from mixed alunite or substituted Al in Fe positions in the jarosite.

The plumbojarosite of the Eryscian mine appears to be of reasonable homogeneity and purity as indicated by X-ray and chemical information. This curve has already been discussed.

The plumbojarosite from the Atalaya claim is of considerable interest in that it is apparently a case of substitution of Al for Fe in the jarosite lattice. The X-ray diffraction pattern shows a shift in several strong lines toward the alunite spacings. An aluminum-substituted member of the jarosite group is to be expected on theoretical grounds but has not been previously reported. The chemical analysis indicates the presence of aluminum. The thermal curve can be interpreted most reasonably as that produced by an aluminum-substituted plumbojarosite. During the initial decomposition, amorphous Fe_2O_3 , Al_2O_3 , and crystalline PbSO_4 , $\text{Fe}_2(\text{SO}_4)_3$ and $\text{Al}_2(\text{SO}_4)_3$ are formed. The Fe_2O_3 crystallizes at slightly higher temperatures to hematite and the amorphous Al_2O_3 goes over to $\alpha\text{-Al}_2\text{O}_3$ at 692°C ., followed rapidly by the ferric sulfate decomposition (733°C .). The final endothermic peak at 874°C . is presumably due to the final $\text{Al}_2(\text{SO}_4)_3$ decomposition.

The Almada, Mexico yellow material begins decomposing at a temperature near that of jarosite. The reason for this anomalous behavior lies in the extremely fine particle size of this specimen. X-ray patterns show the yellow material from Almada to be a mixture of plumbojarosite and argentojarosite in roughly equal concentrations. The small endothermic peak (950°C .) characteristic of the presence of metallic silver is also present. The two argentojarosite specimens from the Tintic Standard mine are similar and may be considered typical of the mineral.

In summary—the thermal characteristics of the jarosite group are such that the presence of thermally active or inactive impurities can be readily detected. Also, if the material is monomineralic, the particular member of the jarosite group is identifiable from the thermal curve. Furthermore, argentojarosite can be detected in intimate intergrowths by the presence of the $900\text{--}950^\circ\text{C}$. melting peak for silver. The potassium jarosite differs from the lead and silver varieties by having a lower temperature for the initiation of the lattice destruction and a higher temperature for the second endothermic peak.

SUBSTITUTION

Theoretically a number of possibilities exist for substitution in the jarosite group. The structure is composed of three main cation positions which in ordinary jarosite are occupied by potassium, iron, and sulfur. The possible replacements based on ionic radii (Palache *et al.*, 1944) are shown in table 2.

TABLE 2

Potassium position		Iron position		Sulfur position	
Ion	Ionic Radii	Ion	Ionic Radii	Ion	Ionic Radii
*Na ⁺	0.98 Å°	*Fe ⁺³	0.67 Å°	*S ⁺⁶	0.29 Å°
*K ⁺	1.38	*Al ⁺³	0.57	*P ⁺⁵	0.34
**Rb ⁺	1.48	Cr ⁺³	0.65	As ⁺⁵	0.47
*Ag ⁺	1.20	Co ⁺³	0.65		
*Pb ⁺²	1.32				
Sr ⁺²	1.18				
Ba ⁺²	1.36				
Ca ⁺²	1.01				
Au ⁺²	1.87				
Hg ⁺²	1.11				
**Ce ⁺³	1.10				

* These cations form known jarosite-alunite minerals.

** These cations form synthetically prepared jarosites (Fairchild, 1933).

The wide range of ionic radii possible in the potassium position is attributed to the relative openness of the structure.

The extent to which substitution is found in these minerals will be determined in large measure by the geochemical environment present during their formation regardless of the substitution theoretically possible. As Hendricks (1937, p. 783) points out, "There is no explanation in the structure for the observation that the various minerals are usually found free of extensive isomorphous replacement."

In this study none of the samples indicates substitution for the sulfate group by either phosphate or arsenate. The substitution of aluminum for iron has been indicated in the specimen from the Atalaya claim and may be present in the Pioche specimen to a lesser extent. No other substitution has been demonstrated. It is entirely conceivable, however, that a chromium jarosite could be formed, if a unique combination of potash-iron-acid-bearing solutions passed through a chromite deposit. The probability of such an unusual set of conditions is so small that it accounts for the absence of this mineral. Complete substitution in the potassium positions by other cations gives rise to the various jarosite minerals. It is interesting to note that analyses in the literature seldom reveal the presence of more than one of the potassium position cations in a single specimen. In the present study partial substitution of silver or lead in jarosite, or of silver in plumbojarosite, and lead in argentojarosite, has not been observed. The one or two plumbojarosite specimens that do give evidence for the pres-

ence of silver probably contain a small quantity of argentojarosite. The striking absence of substitution is evident from X-ray diffraction patterns in the case of the yellow material from Almada, Mexico. Since both argentojarosite and plumbogjarosite are indicated the most reasonable interpretation is the existence of two generations. Because of the low temperature of formation and relative insolubility in dilute acids, it is to be expected that once jarosite has formed in one geochemical environment, any change in the composition of the solutions with regard to the potassium-substituting cation (either Ag or Pb) will not rework the member already formed but simply deposit the new member. Apparently this is the case with the Almada material and may be the situation in the Potosi specimens. In view of the relative solubilities and the sources of lead-bearing as against potash-bearing solutions, it is not too likely that potassium and lead would be present in roughly equal concentrations at the time of formation of the jarosite mineral. As long as the concentrations differed by as much as a 1:20 ratio no appreciable substitution would be detected by inspection of thermal curves or X-ray patterns.

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FOSSIL CUP CORALS FROM THE METAMORPHIC ROCKS OF CENTRAL VERMONT*

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ABSTRACT. Cup corals are herein reported, from phyllite that is interbedded with the crystalline limestones of the Waits River formation, at several localities in central Vermont. The corals, preserved chiefly as silica replacements 1.5±cm. in diameter, are clustered along bedding zones. They are oriented parallel to crenulations in cleavage that cuts across the bedding. A central vesicular zone, septa, and a circumferential wall are distinguishable in the better preserved coral specimens. V. J. Okulitch reports that the corals are probably *Streptolasma*, possibly *S. corniculum* and that therefore they suggest a Middle Ordovician age. This correlation is partly consistent with meager information already at hand, but may be subject to revision as more data become available.

INTRODUCTION

IN June, 1947, while mapping the Montpelier quadrangle in connection with U. S. Geological Survey investigations of talc deposits in Vermont, the writer discovered cup corals at several localities near the city of Montpelier, and also in East Montpelier and Calais townships. These fossils are remarkable for their preservation in phyllite, and are also a rare find in central and eastern Vermont. At the suggestion of Dr. J. B. Reeside, Jr., of the Geological Survey, they were sent to Professor V. J. Okulitch of the University of British Columbia for identification and age determination. The writer is grateful for Professor Okulitch's report quoted here. It is believed that the mode of occurrence of the fossils will be of interest to structural and metamorphic geologists as well as to paleontologists and stratigraphers.

The writer is indebted to C. G. Doll, P. E. Hotz, R. H. Jahns, J. F. Murphy, Professor Okulitch, and Dr. Reeside for critical reading of the manuscript.

PREVIOUS WORK

The rocks that contain the fossils were originally included in the "calcareo-mica schist" of C. B. Adams (1845, pp. 49, 62), later designated the "calciferous mica schist" by Edward Hitchcock, Sr., who described them in the Report on the Geology of Vermont (Hitchcock, *et al.*, 1861, pp. 475-488).

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Subsequently, C. H. Richardson (1898) proposed the name *Washington limestone* for the more calcareous portion of the "calciferous mica schist," but, finding that this name was pre-occupied, he later (1906, pp. 86-90, 115) replaced it with the term *Waits River limestone*. Currier and Jahns (1941, p. 1491) have revised the term "Waits River limestone" to *Waits River formation* to accommodate more correctly the phyllite and other noncalcareous rocks that are abundantly represented in the section.

The various publications of Richardson in the Reports of the Vermont State Geologist have indicated that the "Waits River limestone" is fairly continuous from north to south through the state of Vermont. C. G. Doll and the writer jointly have traced the Waits River formation northward across the International Boundary into the Tomifobia slates and limestones (Clark, 1934, pp. 11-12; Ambrose, 1943) of southern Quebec; H. C. Cooke¹ identifies the Tomifobia formation with the St. Francis series found farther to the northeast in Quebec. Richardson (1898) traced the "Waits River limestone" southward into Massachusetts where the Conway schist (Emerson, 1898, pp. 188-201), contains similar limestone strata. The stratigraphic and structural relationships of the Waits River formation to the Northfield slate and successively older formations to the west have been indicated by Currier and Jahns (1941, pp. 1490-1506). The relationships of these formations to the Gile Mountain formation and associated younger rocks, commonly found to the east, have been noted by C. G. Doll (1945, pp. 16-19).

The Waits River formation and its equivalents in Quebec and Massachusetts have been given age assignments that range from Ordovician to Devonian. Faunal investigations have furnished inconclusive and partly conflicting results, probably inasmuch as the fossil material necessarily is poor because of its occurrence in metamorphic rocks. Currier and Jahns collected fragments of crinoid stems believed to be of "Middle Ordovician or later age" from strata that underlie the Northfield slate (1941, pp. 1501-1502). Richardson (1916, pp. 142-145; 1919, pp. 49-51; Richardson and Camp, 1919, pp. 114-115) reported graptolites from the Northfield slate and Waits River formation, specimens that are believed by Ruedemann

¹ Oral communication, 1949.

(1947, p. 63) to be of both Deepkill and Normanskill age. Doll (1943a) reported crinoids and other forms, which he believes to be of Silurian or possibly Devonian age, from the "Waits River limestone" of northern Vermont and in beds that he assigns² to the upper part of the Waits River formation. He reported also a brachiopod, which he believes to be of Lower Devonian age (1943b), from the Gile Mountain formation (1945, p. 19). Poorly-preserved fossils have been reported from a few other areas in the vicinity of the Waits River formation (Richardson, 1902, p. 94; 1929, p. 245; Richardson and Maynard, 1939, p. 96); they furnish no conclusive evidence as to age, and their exact stratigraphic or geographic positions were not recorded or are uncertain. T. H. Clark reports graptolites with "a Trenton aspect"³ from the Tomifobia formation in Quebec. The St. Francis series of Quebec is reported to contain graptolites of Normanskill age (Cooke, 1937, p. 42). The Conway schist in Massachusetts contains rust-coated cavities that were believed by B. K. Emerson (1898, pp. 200-201) to represent indeterminate fossils.

GEOLOGIC SETTING

The strata in which the corals were discovered form part of the east limb of the Green Mountain anticlinorium, whose axis is coincident with the summit ridge of the Green Mountains about 17 miles to the west. The known fossil localities occur in a belt approximately 2 miles wide that trends north-northeast for about 7 miles from the Winooski River in and east of the city of Montpelier to the vicinity of Bliss Pond in Calais township (fig. 1). This belt parallels the strike of the Waits River formation. The western border of the belt is commonly a little less than half a mile east of the Northfield slate and immediately east of the outcrop of a zone, in the lower portion of the Waits River formation, that is relatively rich in syngenetic pyrite. The average dip of the strata is about 75° W., and both cleavage-bedding relationships and orientation of the corals indicate that in the majority of exposures the tops of the beds face east. Thus the strata are overturned but probably not repeated to an appreciable extent. Discounting repetition, the lowest of the coral-bearing strata are estimated to be

² Oral communication, 1949.

³ Written communication, 1949.

2,000 to 3,000 feet above the base of the Waits River formation, and the fossil zone itself is probably at least 10,000 feet thick. Its eastern (upper) limits have not been determined.

Seven collections were made from the following localities (fig. 1):

1. Montpelier city, 1.35 mi. S. 54° E. of the State House; ledges north of railroad and in line with dam in the Winooski River.
2. East Montpelier township, 0.3 mi. S. 45° W. of school house at East Montpelier Center; east face of ledge about 100 feet west of road.
3. Calais township, 0.8 mi. S. 30° W. of site of No. 7 School; east face of ledge about 200 feet west of road.

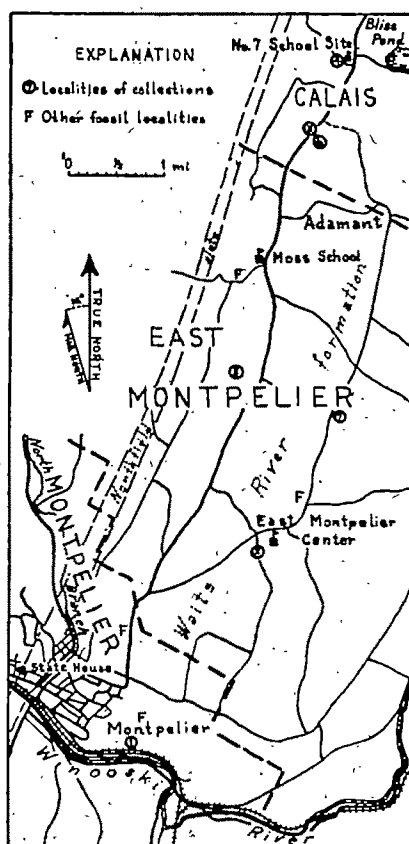


Fig. 1. Index map showing fossil coral localities, Montpelier, East Montpelier, and Calais, Vermont.

4. Calais township, 0.1 mi. due west of site of No. 7 School; at east foot of wooded ledge southwest of bend in road (fossils found in loose fragments).

5. East Montpelier township, 1.1 mi. S. 8° W. of Moss School and about 1,500 feet west of road, within edge of woods near southwest corner of pasture; eastward facing ledge a few feet west of granitic sill.

6. Calais township, 0.85 mi. S. 22° W. of site of No. 7 School and about 400 feet east-southeast of road near center of partly wooded pasture; eastward facing exposure is a few feet west of granitic sill.

7. East Montpelier township, 1.35 mi. N. 28° E. of school at East Montpelier Center and about 300 feet east of road in pasture a little south of fence; east face of ledge.

PETROGRAPHIC AND STRUCTURAL RELATIONS

The rock in which the fossils are commonly preserved is a dark phyllite composed chiefly of sericite and very fine-grained quartz, small amounts of chlorite, and scattered ilmenite plates that are visible to the naked eye. The sericite flakes have a common orientation and form a schistosity parallel to which the cleavage is developed. Crystalline limestone, interbedded with the phyllite, is iron gray on fresh surfaces, but weathers to a brown earthy crust. About one-half to two-thirds of the volume of the limestone is calcite, and the remainder is composed of quartz and minor quantities of muscovite.

Bedding may be traced most favorably where the cleavage crosses it at a relatively high angle and where the fossils, or syngenetic sulfides, distributed parallel to the beds, have preserved stratification as fossiliferous or rusty zones. Bedding is best seen at contacts between the phyllite and the limestone.

The texture of the rocks of the Waits River formation coarsens to the east, and also locally in the vicinity of granitic sills. Near the latter, increased metamorphic effects are quite apparent, particularly the appearance of spotted phyllite with porphyroblasts of biotite and cordierite. The limestone may be whitened and may contain considerable quantities of diopside and titanite.

The near-vertical east faces of phyllite ledges commonly coincide with the planes of bedding, and the cleavage dips westward into these faces at gentler angles (plate 1, fig. 1; text fig. 2). These relations characterize most of the fossil localities. A lineation, formed by fine crenulations in the cleavage, plunges northward in the plane of the cleavage (plate 2, fig. 1; text fig. 2). The calyces of the corals open out easterly at the bedding plane in the direction of the stratigraphic tops of the beds, and taper downward in the plane of the cleavage in such a way that the long axes of the individuals are parallel to the lineation. The corals are commonly flattened in the plane of the cleavage, which parts around them and gives them an eye-like appearance. There is some megascopic evidence that the corals have been rotated; the cleavage that adjoins a few of the individuals forms a helical pattern adjacent to the fossils (plate 2, fig. 1). Too few occurrences of this feature have been observed to indicate whether or not adjacent corals, presumably in a common structural setting, have been rotated in the same direction.

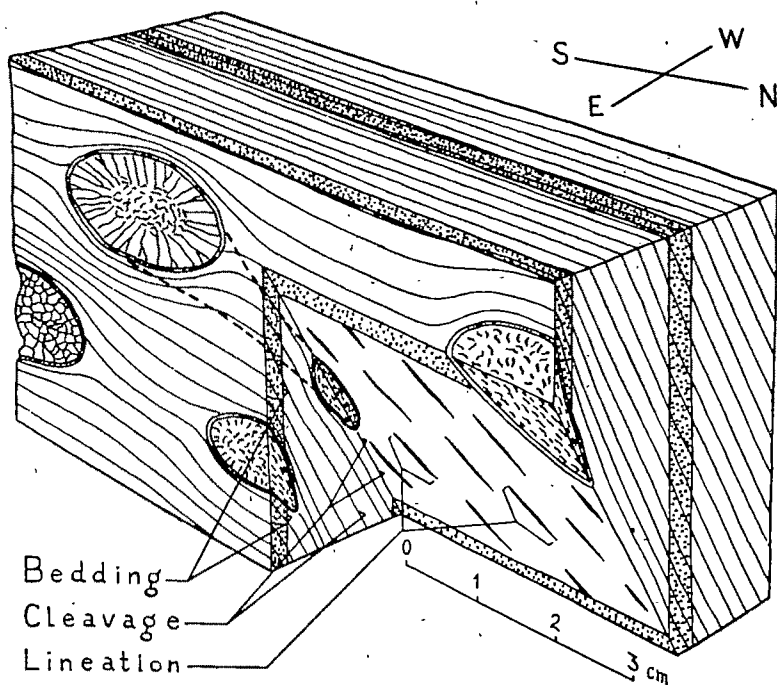


Fig. 2. Block diagram showing the relationship of the fossil corals to bedding, cleavage, and lineation.

The structural relationships indicated by data recorded at the locality of collection No. 7 are typical of most exposures of the Waits River formation in the Montpelier - East Montpelier - Calais belt:

Bedding	Cleavage	Lineation
Strike N. 17° E.	Strike N. 23° E.	Bearing N. 21° W.
Dip 88° W.	Dip 50° W.	Plunge 40°

The strikes of bedding and cleavage are commonly within 10 degrees, as shown here, and are parallel at many localities.

FOSSIL DESCRIPTIONS

The best-preserved corals (plate 1) are those at the locality (fig. 1) from which collection No. 7 (plate 2) was obtained. Hundreds of individuals are exposed on the nearly vertical east face of a ledge that is more than 75 feet long and stands 4 to 5 feet above the pasture. The petrographic and structural relationships of the fossils at this locality are similar to those at other localities. Preservation is related to silicification along comparatively open bedding joints and associated partly calcareous zones. The corals are completely replaced by silica, part of which is iron-stained, and most of the calyces are filled with granular quartz that obscures the fossils. The silicification and quartz filling of the originally calcareous corals are believed to have favored their great resistance to deformation, as compared with the adjacent phyllite. Some individuals show only silica replacement, without development of the quartz filling. From them it has been possible to determine that the fossils are actually corals.

The average corallite is 1.5 cm. in diameter, and is estimated to be 2 to 3 cm. long; its length commonly is difficult to estimate because the greatest amount of silicification, and hence preservation, is in the vicinity of the calyces. The basal portions, distal to the calyces, are delimited with difficulty. Distinguishable in the best-preserved specimens, in which the calyces are not filled with quartz, is an outer zone of radiating septa terminated outwardly by a circumferential wall and connected inwardly with a central vesicular zone in which the septal arrangement is lost. The septa of some specimens appear to bifurcate toward the circumferential wall. Professor Okulitch reports on the fossils as follows:

- "Some of the specimens are undoubtedly cup corals, others show nothing but a reticulated or vesicular mass. The preserva-

tion is such that all finer details of septa, walls, and the central vesicular zone are lost. Some of the apparent structures are in all probability secondary due to partial recrystallization and solution. I do not think that it would be prudent to give the specimens a definite and precise generic and particularly specific name. But considering their size, number and arrangement of septa, and the presence of a somewhat indefinite central vesicular zone, my impression is that the corals are probably *Streptelasma*. The genus *Streptelasma* is very common in the Middle and Upper Ordovician of North America. If the specimens are *S. corniculum*, as appears likely, the age could be from Black River to the top of the Trenton. I do not think that polishing or sectioning of the specimens would give much additional information. As it is, natural weathering gives a three dimensional aspect of their internal structure."

CONCLUSIONS

Satisfactory correlation of the Waits River formation with the stratigraphic sections of other areas must await further field studies and paleontologic data. The Middle Ordovician age suggested by Professor Okulitch is rather consistent with the meager fossil evidence already available and briefly summarized in the forepart of this paper. In view of the poor state of preservation of all fossils thus far reported, as well as of those collected by the author, it should be recognized that future discoveries of fossils, or of new stratigraphic and structural relations, could result in changes in age assignments.

The author is extending the stratigraphic studies of the formations beneath the Waits River formation initiated by Currier and Jahns (1941), and expects to search for additional fossils in the Waits River formation as time permits. Continued search should result in the discovery of fossils that are as well or even better preserved than those already found. All but one of the collections listed were obtained in the course of but one month of routine geologic mapping and several other coral localities (fig. 1) were observed during this period. The area of discovery was restricted to the part of the Waits River formation that lies within the Montpelier quadrangle. Additional search within this quadrangle, as well as in adjoining areas, seems justified.

PLATE 1

Outcrop of phyllite showing fossil cup corals.

Fig. 1. Bedding-cleavage relationships. The hammer handle is in the projected plane of the bedding surface over which the fossils are scattered; the cleavage, which strikes nearly parallel to the bedding but dips into the face of the outcrop, shows on the surface of the cross-joint on the left.

Fig. 2. Close-up view of the bedding surface. The position of the individual corals is indicated by white quartz that fills the coral calyces; a small coral without the quartz filling is directly in line with the 10¾ inch mark on the foot rule. Two poorly defined joints that pass across the upper half of the view are nearly parallel to the cleavage.

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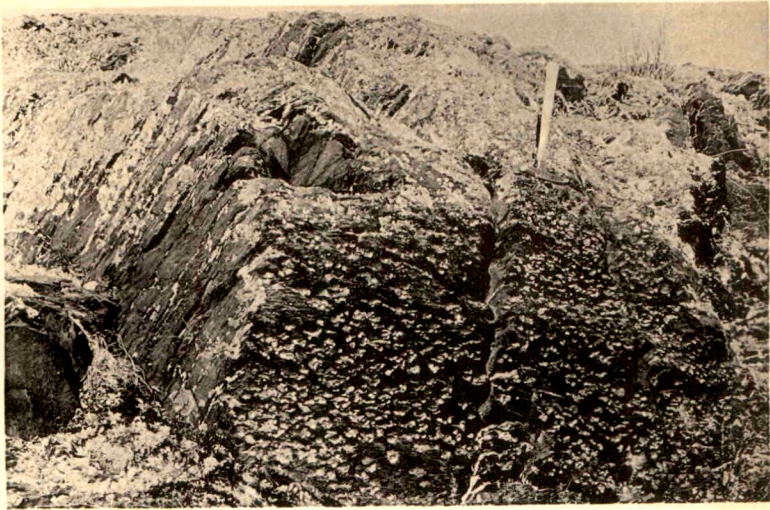


FIG. 1

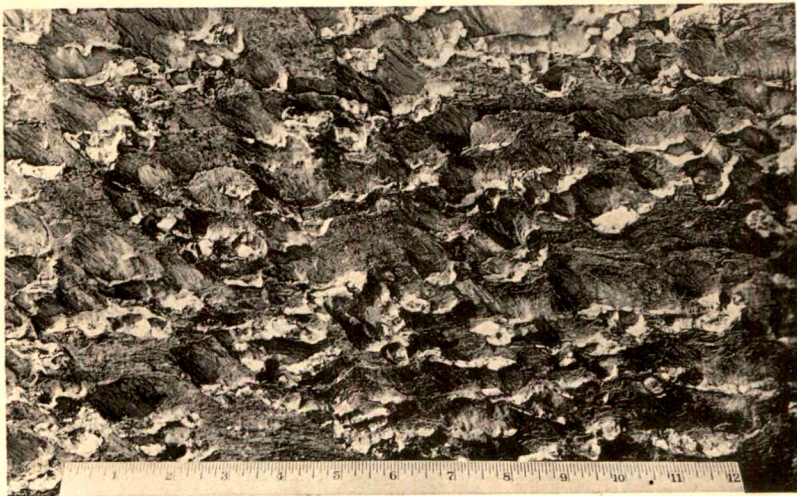


FIG. 2

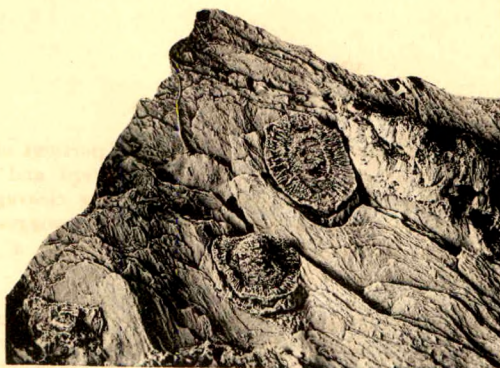


FIG. 1



FIG. 2



FIG. 3



FIG. 5

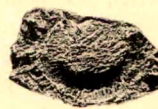


FIG. 6



FIG. 7



FIG. 8

PLATE 2

Detailed full-size views of the cup corals.

Fig. 1. In place in the phyllite. Two corals, the upper portions of which are exposed in the plane of the bedding, taper downward and to the right into the specimen and parallel to crenulations in the cleavage. The helical pattern of the cleavage around the upper individual suggests that it has been rotated counterclockwise. Both individuals show a central vesicular zone, radiating septa, and circumferential wall.

Figs. 2-4. In cleavage fragments of phyllite. These specimens were removed from the outcrop by sliding them out parallel to the lineation; they taper downward, and the cross section of a cleavage fragment, which is eye-shaped in the vicinity of the calyx of the coral, flattens out to a spade-shape near the base. Flattening in the plane of the cleavage is particularly evident in figures 2 and 4. The central vesicular zones are relatively large, and the septa are not as well defined as in figure 1.

Figs. 5-8 — Top views.

5. A coral partly fills a hollow within a cleavage fragment.

6. The central vesicular zone commonly forms a protuberance, as shown in this specimen.

7. The septa in this specimen are absent or poorly formed, and the vesicular zone extends to the circumferential wall.

8. Some of the septa in this specimen seem to bifurcate toward the circumferential wall.

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CLIMATIC FLUCTUATION, A SUGGESTED MEANS FOR THE DEVELOPMENT OF LAKE TERRACES, KUNMING BASIN, CHINA

BENJAMIN A. TATOR

ABSTRACT. The tectonic lake basins of Yunnan Province, southwestern China, contain lake terraces the origin of which appears to be related to climatic fluctuation during the Quaternary. The Kunming Basin, containing Lake K'un-yang, was formerly enclosed but has since been included in the Yangtze drainage system by stream capture. The lake terraces were produced by an alternation of deposition and erosion controlled by variations in rainfall during the Pleistocene intervals. The more arid intervals provided an excess of coarse debris which, by clogging the lake outlet, caused temporary stabilization of the lake level. Deposition of terrace materials on the basin floor resulted. Subsequent increase in precipitation, however, allowed the lake outlet to clear away the alluvial dam and the lake level was lowered. Repetition of this cycle under the influence of continuous regional uplift developed terraces at successively lower positions within the basin.

INTRODUCTION

Location

THE Kunming Area includes a large intermontane basin and its bordering highlands in eastern Yunnan Province, southwestern China (figs. 1 and 2). It is one of a number of similar basins of tectonic origin characteristic of Yunnan, the majority of which were occupied by lacustrine waters during relatively recent geologic past. The Kunming basin still retains a portion of its original water body in Lake K'un-yang. Other lakes, including Fuhsien Hai, Yang-tsung Hai, and Chilu Hai are present in smaller basins located east and south of the Kunming basin.

The rugged topography of Yunnan Province places mountain barriers and deep, often impassable valleys across all approaches to the Kunming Area. Adequate communication with surrounding regions has never been achieved. Deeply dissected mountainous terrain separates the basin from the Yangtze Kiang 80 miles to the north. The Burma border lies about 250 miles to the west, the topography in this direction becoming increasingly mountainous and culminating in the southward continuation of the Himalaya arc along the valleys of the Salween and Mekong rivers. The French Indo-China border is located 150 miles to the south, the surface in this

direction being dissected by a maze of deep canyons. The distance from the Kunming Area to the French Indo-China coast is approximately 400 miles.

Climate

The climate is a subtropical monsoon type, the controlling factor being altitude rather than latitude (Jen, 1948). The lake basin stands at 6400 feet, this elevation producing a more temperate climate than is normal for this latitude in Asia. According to Cressey (1934, pp. 373-374) the average minimum temperature is 4° C. and the average summer maximum is 26° C. Seasons are based on wet and dry contrasts rather than temperature differences. Torrential storms occur from May through October, accounting for most of the yearly average precipitation of approximately 40 inches. Strong southwesterly winds characterize the dry winter months and produce local duststorms where moisture and vegetation are scanty. Some believe these storms to have been active in the topographic development of the basin areas since late Tertiary (Brown, 1914). The advent of cold, arid conditions in the Asiatic interior during the Pleistocene is thought to have increased wind activity in Yunnan. A further inference is that the alternation of wind and water action during the dry and wet seasons has been largely responsible for the thick section of fine and coarse clastics which underlies the basin floors.

PHYSICAL SETTING

Topography

The Kunming basin is an elongate, lacustrine plain with dimensions of approximately 35 miles in a north-south direction and a width of 10 to 12 miles (fig. 1). Lake K'un-yang, approximately 25 miles long and 5 to 7 miles wide, occupies the western half of this plain. The surrounding country is prevailingly mountainous, rising to 8000 feet in some localities, and with the relief reaching 2000 feet. The basins and intervening mountains show a definite northeast-southwest alignment. One particularly high ridge parallels the western edge of Lake K'un-yang, presenting a precipitous escarpment known locally as the Sin Chang Cliffs (fig. 1 and plate 2, fig.

2). A broad alluvial flat, barely above the present lake level, intervenes between the lake and the mountainous country to the north, east and south (plate 1, fig. 2). Several alluvial terrace remnants occur at elevations from 10 to 100 feet above the present basin floor along its eastern side.

Drainage

The basin is drained from the southwestern portion by the P'u-to Ho, tributary to the Yangtze Kiang (fig. 1). This single outlet passes through the high Sin Chang Cliffs in a deep, narrow valley. The direction of flow of this stream is first northwestward and then northward to the Yangtze Kiang. Other, more minor streams, dry during much of the year, drain into the basin from the surrounding highlands. Solution activity in the uplands has produced a near-karst topography in many localities.

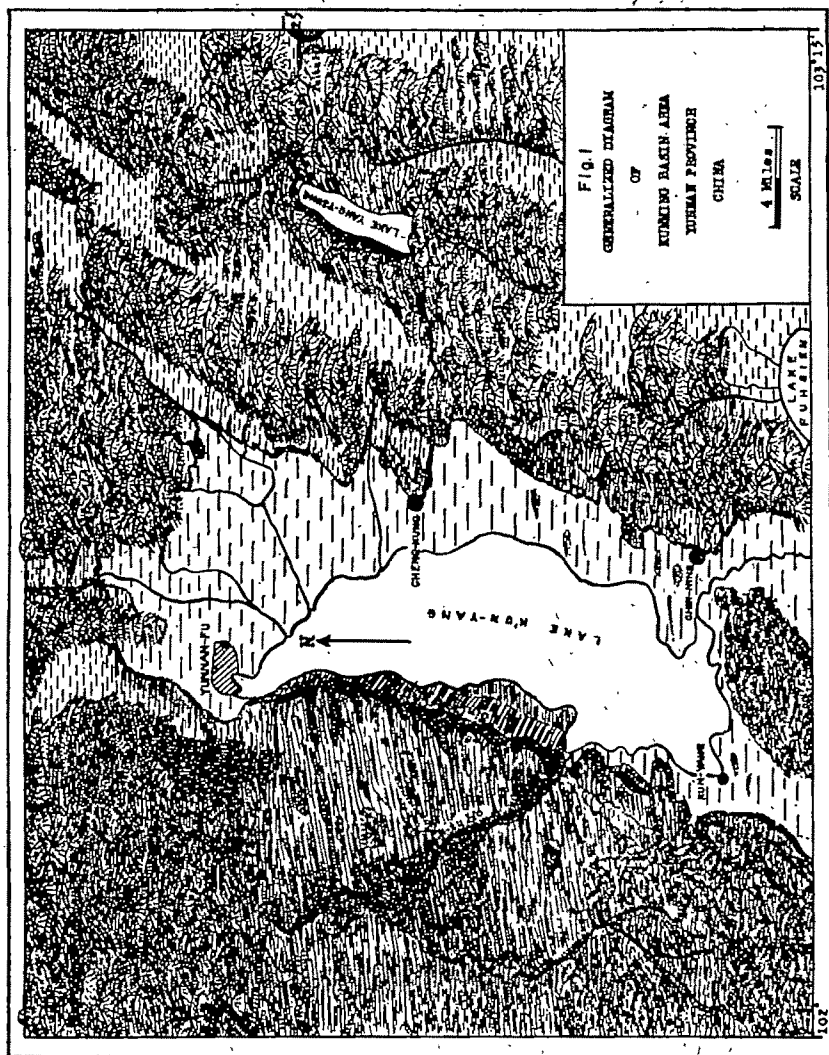
A major drainage divide follows the crests of the ridges east, south, and west of the basin. The runoff east and south of this divide reaches the Peita Ho, tributary to the Hungshui Kiang (fig. 1). Yang-taung Hai, Fuhsien Hai, and Chilu Hai drain into the Peita Ho. The drainage west of this divide is southward into the Yuan Kiang system. Within the basin the runoff is northward into the Yangtze Kiang via the P'u-to Ho, as mentioned above.

An outstanding relief characteristic is the great depth and narrowness of the stream valleys. The P'u-to Ho flows in a precipitous canyon, 2000 feet deep in places. At its juncture with the Yangtze Kiang, relief is in excess of 8000 feet. Minor valleys are also deep and narrow.

It is quite apparent that thorough integration of the drainage has not been accomplished. Lake K'un-yang was originally fed in part by an eastward-flowing P'u-to Ho. This stream was captured by a headward-working tributary of the Yangtze Kiang, reversing the direction of flow and providing an outlet for the lake (fig. 1). Other examples of stream capture are indicated by the barbed appearance of tributary streams in the basin vicinity.

Rock Outcrops

Rocks ranging in age from Cambrian through Quaternary outcrop in the Kunming Area (Brown, 1914). Of these only



Late Paleozoic and Quaternary strata are sufficiently widespread to be of topographic importance. Exposures of Cambrian sandstones and shales, for example, occur only where faulting activity has brought them within the scope of vertical dissection.

Late Paleozoic (Middle Carboniferous) sandstones and limestones form low ridges above the lacustrine plain south of

Lake K'un-yang near Chin-ning and Kun-yang and between Chin-ning and Cheng-kung southeast of the lake (fig. 1). The P'u-to Ho outlet north of Kun-yang is floored with these rocks. Other exposures occur in the basal portions of escarpments north of Yunnan-Fu and west of Lake Yang-tsung.

Most of the country west of the basin is underlain by limestones (Upper Carboniferous), strata also largely responsible for the near-karst topography north of Yunnan-Fu. Exposures of these rocks occur in the base of the Sin Chang Cliffs west of Lake K'un-yang, the upper portion being composed of similar but younger limestones (Permo-Carboniferous) (plate 2, fig. 1). Much of the highland area north, northeast, and east of the lake basin is underlain by the latter limestones with local outcrops of lava, shale, and sandstone.

The basin floor is underlain by Quaternary lacustrine deposits consisting of interfingering layers and lenses of unconsolidated clay, silt, sand, and gravel. Lignitic concentrations occur throughout. Local accumulations of gravel and cobbles indicate deposition by torrential streams. Alluvial fans are present at points of debouchment of stream channels along the basin sides. Finer clastic materials are found in the deltaic projections of the lake shore, as at Yunnan-Fu, Cheng-kung, Chin-ning, and Kun-yang (fig. 1).

Quaternary terraces along the eastern side of the basin are lithologically similar to the more recent deposits of the basin floor. These are dissected remnants of old fluvio-lacustrine plains, each representing an interval of alluvial fan and deltaic construction during a temporary halt in lake-level subsidence. Detailed examination was not possible at the time of collection of data for this paper. However, the undulatory appearance of the terrace surfaces and the character of the deposits lends this thesis greater strength than mere assumption. Additional study may show a relationship between the lake terraces and fluvial terraces further downstream in the Yangtze drainage system.

Observations made in the lower hills along the eastern side of the basin, at somewhat greater elevation than the highest terraces, revealed the presence of disoriented, tilted blocks of thinly bedded, silty clays, sandstones, and lignitic layers of semi-consolidated nature (plate 1, fig. 1). These strata occur at lower elevations than the Paleozoic limestones which con-

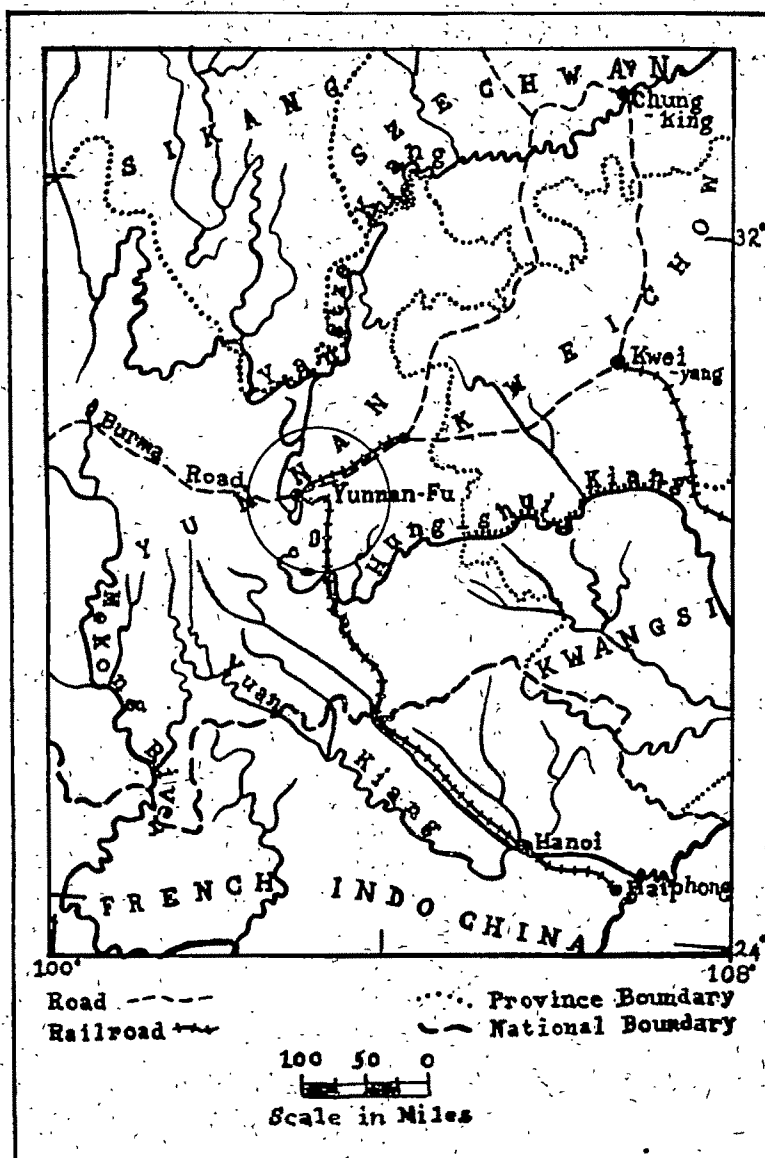


Fig. 2. General map of southwestern China showing major drainage lines and existing communications.

stitute the higher ridges. The beds contain unidentified vertebrate remains and, according to local scientific opinion, are upper Pliocene. The jumbled attitude is the result of faulting.

SUGGESTED PHYSIOGRAPHIC DEVELOPMENT

The rugged, deeply dissected terrain, with steep, relatively fresh-appearing escarpments, favors belief that the Kunming Area is tectonically active at present. Further evidence is found in the modern earthquake record (Cressey, 1934, p. 36). The structural trends of the region, according to Lee (1939, p. 309), are approximately north-northeast and south-southwest, this also being the alignment of the lake basins. The south China region is believed by Lee to have been folded and elevated in late Mesozoic time, the modern basins being of tectonic origin aligned along the axes of folding.

Brown (1914, p. 115) postulated a late Tertiary age for the inception of the modern topographic development, the lake basins having been formed by faulting toward the close of Pliocene. Perhaps old zones of weakness produced by the late Mesozoic folding provided a locale for late Pliocene tectonics. The present bold relief is the result of uplift and faulting, with accompanying stimulation of erosional agencies down through the present. Deprat, as quoted by Lee (1939, p. 206), claims abundant evidence for recent uplift in Yunnan of as much as 6500 feet, though this figure would seem excessive. There can be little doubt, however, that uplift is occurring. The narrow, deep valleys, a dominant topographic element in the region, indicate a continuous stimulus to stream erosion. Furthermore, the lake basins are being tapped and gradually drained as the deepening valleys encroach into these formerly enclosed areas. The steep, 2000-foot Sin Chang Cliffs, in the present writer's opinion, represents only slight modification of a fault scarp along which faulting may still be potential (plate 2, fig. 2). The tilted blocks of Tertiary sediment (Pliocene ?) along the eastern side of the basin show that faulting occurred subsequent to deposition of these strata.

Brown (1914, pp. 118-119) recognized evidence for several stages in the tectonic and erosional history of the region. He cited an accordance of summits east of Lake K'un-yang as representative of a late Pliocene erosion surface, the Tang-hien erosional stage of Willis (1907, p. 99). A rather noticeable widening in the upper portion of the P'u-to Ho valley walls is also pointed to as a relic of this stage. This interval was presumably one of broad valley development which, accord-

PLATE 1



Fig. 1. Panorama of the Kunming basin from the east. The high rimming hills are visible in the background. Late Tertiary sediments (Pliocene ?) occupy the immediate foreground.

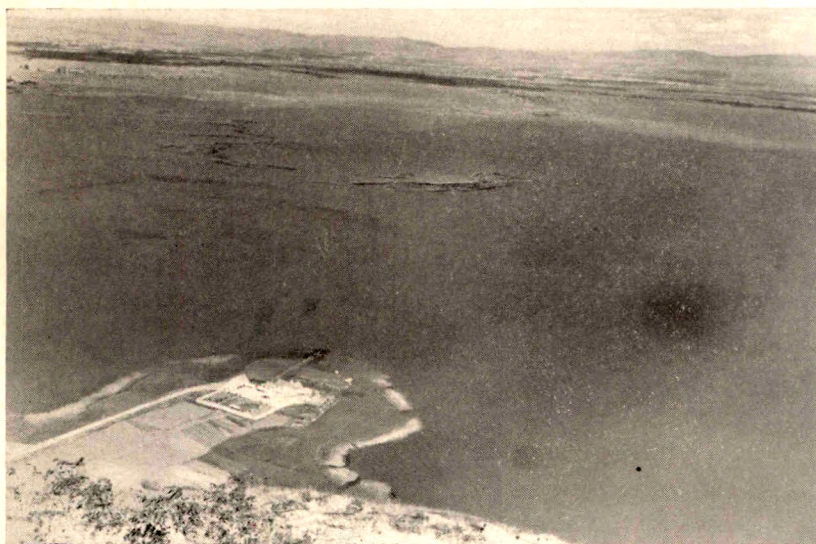


Fig. 2. View eastward from the Sin Chang Cliffs across Lake K'un-yang. The flat lacustrine plain with terrace remnants standing slightly higher is visible in the background.

4

PLATE 2



Fig. 1. Steeply westward-dipping Permo-Carboniferous limestones in the upper portion of the Sin Chang Cliffs west of Lake K'un-yang.



Fig. 2. View south along the Sin Chang Cliffs which rim the western edge of Lake K'un-yang. This escarpment is a fault scarp only slightly modified by erosion. The outcropping strata, Permo-Carboniferous limestones, dip westward into the face of the cliff.

ing to Brown, was terminated by faulting and basin development. In early Pleistocene these basins accumulated lacustrine and fluvial deposits, this being the Hinchou aggradational stage of Willis. This phase is reputed to be in progress at present in the Yunnan region.

The present uplift and drainage adjustment, placed by Brown in the Fon Ho stage (Willis, 1907), may have had its origin in late Pliocene or early Pleistocene. The establishment of drainage systems, deepening of valleys with uplift, and the tapping of the lake basins are the results of this activity. The diversion of Lake K'un-yang into the Yangtze Kiang system, as well as capture of the Yang-tsung, Fuhsien, and Chilu lake drainages, are thought to have been part of this process.

Deprat (Brown, 1914, p. 122) contended that in eastern Yunnan the interval from late Pliocene to the present is divisible into five erosional episodes, separated by periods of relative stability. The present writer does not have sufficiently detailed evidence to refute or support this contention. Critical examination of the Yunnan lake terraces should divulge important facts. A thorough study of the hydrographic development of late Tertiary and Quaternary time is needed.

A relationship suggested is the correlation of lake terrace development with regional climatic fluctuations. Harland (1943), working in western Szechwan north of Yunnan Province, found evidence favoring climatic change during the Pleistocene. Lee (1939, pp. 367-399) also favored this view. Cotton (1944, pp. 272-274), in review of a paper by Richardson (1943) concerned with terraces in western Szechwan, suggested that the terrace gravels along the river valleys may have been deposited during the moist intervals when the supply of debris to the drainage was at a maximum. As precipitation decreased in a subsequent drier interval vertical incision of these deposits occurred. The increased erosive power of the runoff, despite a decrease in rainfall, is attributed to the lessening in quantity of debris supplied by weathering. Repetition of such alternating conditions, along with continuous uplift, resulted in terracing of the valley bottom deposits.

The present writer is in sharp disagreement with this suggested sequence of events. Field data gathered in somewhat similar climatic regions in North America fosters a different view (Tator, 1949). In a region of continuous uplift moist

intervals are times of increased drainage incision, the runoff being less hampered by excess of clastic load. Interstream slopes are temporarily stabilized by the increase in vegetative cover. Chemically controlled weathering processes predominate, the result being that the products are of finer nature. Runoff, fed by the more uniform precipitation, is constant. Drainage lines, unhindered by the clogging effect of coarse debris, are able to maintain permanent channels. On the other hand, minimum downcutting prevails under arid conditions. Decrease in precipitation reduces the vegetative cover thereby decreasing the stability of slopes. Physically controlled weathering produces coarse detrital fragments. Rainfall is less uniform, in fact, is usually torrential and of spasmodic occurrence. Runoff is intermittent and the drainage lines become choked with debris. The streams experience difficulty in maintaining a single line of flow, the latter being a requirement for deep valley incision.

Such could have been the history of the development of the Kunming basin terraces. Intervals of greater moisture caused drainage incision and lowered the lake level. Greater aridity, however, temporarily stabilized the lake level as the outlet became clogged with debris, causing accumulations of fluvio-lacustrine material on the floor of the basin. A succeeding, more humid interval then led to clearing of the outlet and lowering of the lake level. Repetition of this process may have yielded the terrace sequence. The vertical spacing between successive terraces would be controlled by the rate of uplift and the duration of the moist episode whereas the thickness of the individual terrace deposits would indicate the length of the drier climatic phases.

It is believed that the pre-Pleistocene climate in this part of Asia was arid to semi-arid. The incidence of glaciation was brought about by increased precipitation on the higher mountains of western China. It is not illogical to expect that peripheral areas to the south and east of the centers of ice accumulation must also have been affected. Thus, while the glacial stages were perhaps times of increased precipitation, the interglacial stages may have been times of climatic shift toward normal, or aridity.

SUMMARY

The Kunming basin includes a broad lacustrine plain fringed by lake terraces and enclosed by rugged, mountainous terrain. The surrounding highlands are underlain for the most part by late Paleozoic limestones, dissection of which has produced a near-karst topography. This region has been orogenically active since late Pliocene and uplift is still in progress. The basin formed in late Pliocene or early Pleistocene along structural trends established during the late Mesozoic. Capture of the drainage of the basin was accomplished by a tributary of the Yangtze Kiang system in early Pleistocene. Under the influence of continuous uplift and moist climatic intervals, perhaps during the glacial stages, the level of Lake K'un-yang has been progressively lowered. Each lake terrace represents an interval of temporary stabilization of lake level due to alluvial damming of the outlet under a more arid climatic regime. It is felt that the more arid episodes may correlate with interglacial stages. If this sequence of events should prove adequate to account for the Kunming basin terraces it should also be applicable to the other basins of southwestern China.

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DISCUSSION

A paper entitled "Processes of Erosion on Steep Slopes of Oahu, Hawaii"; by Sidney E. White, was published in the March, 1949, issue of this Journal, pp: 168-186. This paper is a condensation of a thesis which briefly describes Oahu, its Koolau Range, and in particular gives a discussion of the factors thought responsible for the steep-walled, theater-like valleys on its leeward side. Manoa Valley is selected as typical and discussed in detail. Much of the article consists of quotations or rephrased statements drawn from Davis, Cotton, and Hinds on geography, Stearns, Vaksvik, and Wentworth on geology, Carson, Jones, and MacCaughy on meteorology, and MacCaughy on ecology. Nowhere in the paper is any statement as to how many trips were made by White or how much time over what period was spent in his study of Manoa Valley. The impression in Honolulu is that the period White spent in these field studies, while in war service, was brief.

An account of the vegetation of Oahu is given, by abstracting to two paragraphs, material from MacCaughy's report on Manoa (1917). White continues (p. 178), "Other leeward valleys may be divided into similar zones." Some may and some may not, due to the strikingly different microclimatic and corresponding ecologic zones on Oahu. It would have been better to refer to actual studies of such valleys, as that by Hosaka on Kipapa Gulch (1937), and that by Egler on arid southeastern Oahu (1947), instead of assuming that all leeward valleys of the Koolau Range had a similar ecologic zonation. His inference that they are all alike is far from the fact.

White's account of the general geology, and description, mapping, and figuring of the geography is largely drawn from dependable sources, and I will not challenge it. On the other hand, after twenty-one years of residence in Manoa Valley and much field work, research, and teaching of botany and ecology as evidenced in the Hawaiian Islands, I feel impelled to deny White's statements of ecological facts and to differ from his conclusions. His main thesis is that on steep slopes in the mountains in the high rainfall belt, the typical succession is (p. 182) as follows: "(1) fresh bedrock exposed; (2) the establishment and succession of mosses, plants, ferns, and trees to the culmination of maximum plant relationships possible, with accompanying soil development to great depths; (3) long and continued use of all available soluble minerals and organic matter; (4) final exhaustion of the soil mantle with deterioration of the plant societies, and alteration to a degenerate growth of grasses; (5) desiccation and hardening of the mass of soil, decaying litter, and rotting humus; (6) instability of the mass of debris produced during prolonged rainfall; and (7) catastrophic avalanching exposing fresh bedrock slopes again."

White's inspiration seems to have come from Freise, a geographer,

who announced in 1988 observing a succession from granite, to forest, to a decadent forest on exhausted soil, to grass,—then avalanching to bedrock. Not having visited the particular granite mountain in Brazil, I cannot express an opinion on its vegetational succession. However, in my own travels and explorations, and I have studied many granite mountains, I know of no place on granite or any other rock where an undisturbed natural forest exhausts its own soil and starves itself out, and is then replaced by grasses. Furthermore, it is not clear to a plant ecologist just what White has in mind when he refers to the grass stage as "a degenerate growth of grasses." A recent scholarly taxonomist, Hutchinson (1984, p. 7), places them at the apex of an upper branch of the family tree of the Monocotyledones. In growth and production, instead of degeneracy, they show great self-sufficiency and adequacy to perpetuate themselves, to nourish themselves, and largely to feed the human race and most grazing animals.

White does not state his reason for reporting in detail only on Manoa Valley. Other more remote valleys would have been more primitive. Of course, Manoa Valley is easy of access, with paved roads almost to the talus slopes, two bus lines for transportation, etc., but as it is near the center of the city of Honolulu, it has, in the last 150 years, suffered from the depredations of man and his domestic animals. The forests have been much reduced in area, depleted, invaded by weeds and exotics, heavily grazed by horses, cattle, and goats, and in areas deforested by the abundant feral pigs. Deforested areas, even on the high, rainy slopes, are often densely vegetated by grass and herbaceous weeds or ferns, but these do not play the important part in initiating landslides (soil avalanches) that White asserts.

White says (pp. 180-181) of the valley head, "Some parts of the slopes are mantled with a thick soil and well-developed plant society, other parts with thick soil and stunted, scrubby grass growth. Certain other sections maintain no soil at all, but instead are sheathed with yellow-brown mud so thin that layered volcanic cinders can be seen beneath. The soil and vegetation on the slopes are in various stages of development from youthful thin soil to maturely developed thick soil, and old thick soil. No ecologic zoning can be distinguished; distribution of variegated patches of vegetation has no obvious relation to topography or climate." White seems fond of an ecological approach, but seems to have little familiarity with its details or meaning. He certainly seems to dislike grasses, but it should be pointed out that a grassy growth can be a well-developed plant society. He does not explain his view that mud is not soil, nor how thin, transparent mud remains on top of bedded volcanic cinders. In reference to his concluding sentence of the paragraph quoted above, as to there being no zoning

and no relation between the vegetation and topography and climate, well—the only comment I can make is that it is not so.

Landslides on the steep forested slopes do occur and the figures quoted by White are striking and significant. They were published by Wentworth following eight years of intensive field work. Certainly landslides play a part in soil movement from steep upper slopes to the gentle valley floor below. The slides are seen in many places, mostly on steep slopes of 40° or more, but they often occur starting in and cutting a strip right out of a healthy, vigorous, virgin, climax forest. After the slide, the invading vegetation of the secondary succession is often rich in grasses, as *Paspalum conjugatum*, etc., but often of other weeds, as *Erechtites hieracifolia*, and *Cuphea carthagenensis*, or of indigenous vines, shrubs, or trees, as *Phyllostegia grandiflora*, *Perrottetia sandwicensis*, *Pipturus albidus*, *Dicranopteris linearis*, *Lycopodium cernuum*, *Scaevola mollis*, *Metrosideros collina*, etc., depending on the habitat, the surrounding vegetation, and source of seeds.

The conditions that cause landslides (soil avalanches),—probably a rainy period that has saturated the soil, followed by torrential rains (such as 5 inches per hour) and high winds, cause landslides on the very steep valley walls, whatever the vegetation, whether thin soil with little vegetation, grasslands, open forest invaded by weeds, or dense virgin forests which show no sign of self-starvation.

My final comment on White's paper is that it contains little original material other than his hypothesis on plant succession as the cause of avalanching on steep basaltic head walls of Manoa Valley. He gives no verifiable data of his own on plant succession or indication that he could recognize one plant from another of the list that he apparently compiled from MacCaughy, or that he has any competence to judge and interpret the stages of a plant succession in Hawaiian vegetation. His hypothesis that avalanching is the result of soil exhaustion by the rain forest which suffers self-destruction and is then succeeded by a "degenerate growth of grasses" which permits soil avalanching is, in my opinion, unproven and is contrary to all that is known of plant succession in Manoa Valley and the Hawaiian Islands.

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REPLY

Response to the paper by S. E. White on the processes of erosion on the steep slopes of Oahu, Hawaii (1949), on the whole, has been favorable. The objections offered by Harold St. John in the preceding discussion present an appropriate opportunity to discuss further the problems of slope erosion in tropical and semitropical regions.

As stated in the introduction to White's paper (p. 170), a brief discussion of the climate, vegetation, and soil of Oahu was reviewed for possible comparison with other tropical and semitropical regions by readers not familiar with the Hawaiian Islands. Under no circumstances was this review of the literature intended to convey originality. It was carefully and completely documented, as St. John's discussion testifies.

The interrupted nature of the field work in the region was a consequence of wartime conditions. Time was not available to organize extended trips, to visit the other Hawaiian Islands, or to descend the cliffs at the heads of all the theaterlike valleys, inasmuch as White lived in Manoa Valley a total of seven months compared to St. John's twenty-one years.

The problems raised by Stearns and Vaksvik (1935), Stearns and Macdonald (1947), Wentworth (1928), Wentworth and Winchell (1947), and White concerning slope erosion in the Hawaiian Islands have not yet been discussed or answered. Some of these problems are here rephrased and summarized.

1. "The talus veneered bedrock slopes in the leeward valleys may be increasing in width at the expense of the cliffs. If this is true, the erosional processes which produced the steep cliffs are no longer as operative as in the past." (White, 1949, p. 174). Are the talus veneered bedrock slopes gaining in area and importance to the disadvantage of the steep cliffs?

2. "... the presence of hydrophytic mosses growing on the face of the cliffs along the course of the falls in the leeward valleys studied suggests the inability of the falls to incise on the face of these cliffs today." (p. 176) Are the high waterfalls no longer actively incising canyons in the bedrock today? If this is true, what changes in stream regimen are responsible for the reduced effectiveness of such erosion?

3. "Cliffs rim the heads of the valleys, a few being 200 to 300 feet high with 70 to 80 degree slopes. Above these cliffs, hanging valleys open upwards and extend back to the main summit ridges of the Range. The sides of these hanging valleys often have slopes of 45 to 65 degrees." (pp. 174-175) Do the hanging valleys above the steep cliffs indicate an older period of greater erosion by the main streams?

4. "A considerable amount of talus veneers the bedrock slopes at

the foot of the cliffs and occupies the floors of the upper valleys. This suggests that erosion is no longer as active as it was in the past, and that changes have occurred which prevent streams from keeping the upper valley floors clear." (pp. 176-177) Does the present condition of the upper valley floors indicate climatic change, general reduction of mountain heights by erosion, or reflect the effect of recent island submergence? What combination of these or other factors has produced this result, and who will advance the statistical information for proof?

5. Wentworth in 1928 (p. 895) summarized the reasons for the great amount of chemical weathering that occurs. "The very great porosity of the Hawaiian rocks, the high average rainfall, the relative ease of decomposition of the minerals composing the basalts, and the high mean annual temperature combine to produce very rapid chemical weathering in the islands, a condition shared, of course, with many other tropical regions." To what extent is the incision of valleys on Oahu and elsewhere dependent upon these factors? Does the more active chemical weathering near the water table level control the configuration of the theaterlike valleys or barrancas?

6. The release of confined water in the dike complex in the Koolau dome (or in any volcanic dome), tapped by both tributary and master streams, as mentioned by Stearns, (1935, p. 25), adds to the perennial water supply and accelerates stream capture. How much does this additional water supply affect headward erosion? Will it account for the incision of certain valleys and not for others?

7. "Captured tributaries entering a master stream form a rim of coalescing plunge pools about the amphitheater wall at the break in the stream gradient. The narrow ridges between the plunge pools are undercut and fall by their own weight . . ." How effective is plunge pool action in the development of a theaterlike valley or barranca where captured tributaries are not involved?

9. Macdonald (1947, pp. 77-78), in discussing the amount of Na, SO_4 , Mg, and Ca in the ground water of a drilled well from the island of Molokai, states that these radicles "cannot be solely the result of mixing of pure fresh water with sea water. In part, they have probably been derived by solution from the enclosing rocks. The high temperature of the water in that well . . . suggests, however, heating of the ground water by rising volcanic volatiles, and some of the dissolved material has probably been brought upward with the volatiles." Here is an attempt to identify the sources of solids in the ground water in which some are derived by solution from the volcanic rocks. Yet how important is solution in the removal of decayed material, and in land reduction?

9. "If sufficient soil, muddy particles, and decomposed rock

debris are carried out from beneath large enough areas of thick matted masses of plants, the forest is thereby lowered onto less decomposed bedrock. Further chemical decomposition will occur, and the surface of solid bedrock beneath the talus thus becomes weathered down to a lower level." (White, 1949, p. 179) Mud flows in the coastal mountains of Brazil break out through the forest floor and thus lower the vegetation onto relatively fresh bedrock beneath. To what extent is this process present in the Hawaiian Islands? What statistical evidence can be advanced to substantiate the effectiveness of this method of erosion under semi-tropical conditions?

10. Movement of small particles of weathered volcanic rocks across steep slopes is important in the reduction of mountain areas. What is the relative significance of water transport, soil flow and soil creep on the slopes of various degrees both in the Hawaiian Islands and elsewhere?

11. Wentworth and Winchell (1947, p. 68) stated that soils may develop a pelletlike structure which renders them resistant to erosion. This resistance, in addition to a heavy forest cover, helps to maintain a thick soil even on very steep slopes. "Locally the deeper weathered material becomes rammed into a compact mass which can stand in steep slopes." What effect does sublatterite development have on the maintenance of steep slopes? The sublatterite soil develops on lower slopes where oxidation and accumulation of iron occur. With the lower temperature and greater rainfall, reducing conditions and the loss of iron are possible on upper slopes. Is soil flow and soil creep hindered on lower slopes by tight sublatteritic soil and relatively favored on upper slopes? What are the limits for slopes produced by avalanching and mass movements below which such processes of erosion do not occur?

12. The soil and vegetation on the steep cliffs is in various stages of development. Depth of soil varies from thick soil with a well-developed plant society to a thin "soil" so thin that the texture of layered volcanics can be seen through the weathered cover. It is assumed that the differences in soil thickness result from differential soil removal, partly by avalanching. What specific influences have plants in generating or delaying mass movements of the soil?

13. "... maintenance of the slopes has depended upon avalanching as a method of erosion in the past, and ... avalanching and mass movement of particles of weathered rock debris control the recession of the steep slopes today." (White, 1949, p. 181). Avalanching is significant in slope reduction in the Hawaiian Islands, but whether less or more today than in the past is still to be determined. White properly stated, "Any further argumentation would be

pure speculation at this writing; proof of such erosion for the past will be revealed only by further field work." (p. 182).

To repeat again, there is a great need for additional, accurate, discriminating and reported investigation of the processes of slope erosion in all climatic regions. Constructive response from all sciences is essential for the solution of the many problems suggested herein for consideration. White's paper is but a small contribution, his start in the direction toward a study of erosion in semitropical regions. If it has attracted attention to the lack of data regarding the mechanics of slope erosion, even among a small group, its publication will have been justified.

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REVIEWS

Mechanics, Statistics and Dynamics; by MERIT SCOTT. New York, 1949 (McGraw-Hill Book Co., Inc., \$4.50).—If the present trend in teaching physical dynamics can be characterized in a single phrase it might be "back to fundamentals," and several excellent texts epitomizing this trend have appeared in the last few years. The reasons for this reaction are many: the enormous increase in material to be taught and the correspondingly diminished time devoted to dynamics, the necessity of putting dynamics into its more general forms for the purposes of quantum theory, the discrediting of mechanism and the loss of fascination for dynamics per se, and others. It is with some surprise, then, that one scans the present text, for by the author's admission it is modeled upon the authors of another era. Here we find the detailed treatments of the many and complicated problems so dear to the Victorians, whereas general principles and methods fill subsidiary roles. While I cannot condemn the book in the field in which the author chooses to operate, I find it out of tune with the times, excellent as a reference text, but not fitted to the needs of the present student of physics who must master the principles of dynamics in its general form.

ROBERT BERINGER

Principles of a New Energy Mechanics; by JAKOB MANDELKER. Pp. viii, 78. New York, 1949 (Philosophical Library, \$3.75).—The present thin volume adds itself to the list of critiques of relativity theory which were so numerous two decades ago. As is usual the author twists one of the relativity postulates in a slightly different way and unleashes a new set of dynamical formulae. The reviewer does not hold with the deductions obtained thereby.

ROBERT BERINGER

Basic Theories of Physics: Mechanics and Electrodynamics; by PETER G. BERGMANN. Pp. viii, 280. New York, 1949 (Prentice-Hall, Inc., \$3.75).—The revolution in physics which dates from the successes of relativity theory and quantum mechanics is only now recasting the basic instruction of graduate students, and the full integration of these changes into elementary teaching is hardly begun. True, various specialty courses are offered in the new theories together with phenomenological reviews of their experimental bases, but the student is likely to find that his training in classical physics has been directed toward nineteenth century objectives, and he undergoes an abrupt transition to the philosophy and analytic methods of the newer disciplines. The present book is apparently designed to soften this transition and to prepare the student more fully for the modern theories. Mechanics is developed from New-

ton's laws, and is carried through analytic dynamics, the mechanics of deformable bodies, and hydrodynamics. Tensor notation is introduced at an early stage and mathematical sections are interspersed throughout. The notation alone is quite unique in books at this level. In the second part electrodynamics is developed through the Maxwell equations and the theory of special relativity. Here the approach is fairly standard but the critical appraisal of the equations and the emphasis on those features most basic to later study are carefully conceived and should be most rewarding. Chapters on wave propagation and the electrodynamical aspects of optics conclude the text. The clarity of exposition and selection of topics is uniformly good, and the interpretative sidelights are excellent. Of these latter, the discussion of the incompatibility of mechanical and field theories impresses me most. My only criticism on a first reading is in the matter of proofs which are sometimes a trifle too elegant or foreshortened.

ROBERT BERINGER

The Crystalline State. Vol. I, A General Survey; by W. L. BRAGG. Pp. 352; 187 figs. Third printing, London, 1949 (G. Bell & Sons, \$8.50).—In 1933 appeared the first volume of an ambitious trilogy, *The Crystalline State*. This volume, entitled *A General Survey*, by W. L. Bragg, was to serve as a general introduction to two more highly specialized volumes prepared by other experts. For various reasons, only Vol. I appeared in print. Recently, however, this almost forgotten project received a new lease on life when an author was found for Vol. II, on X-ray optics. Vol. III still seems to be in the embryo stage. Advantage has been taken of the appearance of the second volume to reprint the first.

It is unfortunate that the opportunity to bring the old volume up to date was not taken at the same time. No references later than 1932 appear, except in the two-page bibliography; prospective purchasers, who might be under the impression that they can buy a revised edition, should look again. Moreover, the price seems unduly high, and the cost is not reflected in a first-rate publishing job. For example, Fig. 75 in the review copy, showing radii of atoms in metals, is almost illegible; there seems to have been an ink shortage during the printing of Fig. 77 and 78 (AX and AX₂ Structures).

When all is said and done, however, the book remains perhaps the best elementary introduction to X-rays and crystal structure. Most of it could be readily understood by a bright undergraduate. Indeed, the undergraduate might also make the surprising discovery that profound scholarship in science is not, of itself, a bar to brilliant writing.

VICTOR GILPIN

Surface Active Agents, Their Chemistry and Technology; by A. M. SCHWARTZ and J. A. PERRY. Pp. xi, 579; 51 figs. New York, 1949 (Interscience Publishers, Inc., \$10.00).—This book concerns those solutes which greatly lower the surface energy of their solvents; the commonest examples of these solutes are, of course, detergents and wetting agents. Here is an exhaustive survey of all the applicable theories and a description of all the practical aspects, including a useful and original classification of surface active agents, methods for measurement and evaluation of their properties, preparative methods and uses.

The authors have aimed at universal appeal by devoting a section to nearly every field connected with surface activity. They apparently hope thereby to interest everybody, all the way from the academic physical chemist to the "Dreft" salesman. There is, therefore, the possibility that each potential and specialized reader might seek his desired information from more specialized sources, but no doubt there is a large middle group of workers who will find here a wonderful time-saver, a bibliography-with-interpretations, covering the length and breadth of a highly fertile field (albeit a somewhat less than fascinating field when regarded in such complete and magnified detail).

The section on "the physical chemistry of surface active agents in theory and practice" should be strongly recommended to any interested person who is not thoroughly familiar with this branch of physical chemistry. In this section are to be found some original thoughts which should be of permanent value in the field and in which may reside the most lasting value of this effort.

Far from leading one through scientific adventure, this practical book is nevertheless extremely useful. It is an exhaustive exposition—exhaustive to a very reasonable degree—of all possible considerations of theory and practice in the fields of wetting agents, detergents and emulsifiers, and it will probably become a standard reference and bibliography text.

ELLIOT S. PIERCE

Diamond Tools; by PAUL GRODZINSKI. Pp. xvi, v-viii, 392; 222 figs., 61 tables. London and New York, 1944 (20/s, N. A. G. Press; \$4.50, Anton Smit and Company).—This volume packs many data into a small space. It includes descriptive chapters with bibliographies on the following subjects: diamond production and trade; diamond as a technical material; diamond and other jewel bearings; hardness testers; grinding-wheel dressers; tools for machining metal; machining of glass; machining of building stone; rock drilling; engraving; wire dies; abrasive powders. Many industrial uses (and

limitations) of diamond are described with great detail for the finest points of technique.

Mr. Gródzinski has written much on various aspects of the subject; this book adds to, and thoroughly summarizes, his previous writings.

HORACE WINCHELL

The Boylston Street Fishweir II; by ELSO S. BARGHOORN, PAUL S. CONGER, SHELDON JUDSON, FRED B. PHLEGER, and L. R. WILSON; edited by FREDERICK JOHNSON. (Papers of the Robert S. Peabody Foundation for Archaeology, Vol. 4, No. 1.) Pp. 188; 14 plates, 15 figs., and 17 tables. Andover, Mass., 1949 (\$2.00).—Discovery in 1946 of part of an Indian fishweir in excavations for the John Hancock Life Insurance Company building on Stuart Street, Boston, has made possible a continuation of the studies of the same or a similar weir uncovered in 1939 during construction of the New England Mutual Life Insurance Company building on Boylston Street. The new studies confirm that the fishweir, whose cultural affiliations are not known, was in use about 2,500 years ago, more or less, when the sea was rising relative to the land towards its present level.

The current studies revolve around a core bored to bed rock beneath the fishweir. Primarily through an analysis of the stratigraphy represented in this core, Conger is able in a discussion of the Pleistocene geology of the Boston area to distinguish two local substages of the Wisconsin glaciation and to correlate these with changes in relative sea level. Studies of the paleobotanical material by Barghoorn, of the micro-fossils by Wilson, of the Foraminifera by Phleger, and of the diatoms by Conger provide additional information concerning the environment before, during, and after the succession of sub-stages. Most of these data refer to the time before the fishweir was constructed, but they also indicate, contrary to some previous inferences, that the climate was no warmer when the weir was in use than it is today.

IRVING ROUSE

Ancient Man in North America; by H. M. WORMINGTON. (Popular Publications, The Denver Museum of Natural History, No. 4). Pp. 198; 21 figs., 2 tables. Denver, 1949 (\$1.50, paper bound; \$2.50, cloth bound).—This third edition of the most comprehensive summary of the subject of Early Man in America has been revised from previous editions published in 1939 and 1944. That the number of pages has increased from 89 to 198 is an indication of the amount of research on the subject in the last decade.

The organization of the previous editions is maintained: (1) a description of the major flint and ground stone industries for which

there is geological evidence of antiquity; (2) an areal survey of the sites in which these industries have been found, with the evidence for dating them; (3) a summary of the finds of human skeletal material for which antiquity has been claimed; and (4) a theoretical discussion of the peopling of the New World. While the book is written for the layman and undergraduate student, it is technically accurate and provides an excellent introduction to the subject for any non-specialist.

The author has made a special effort to include the latest, unpublished research and, as a result, the current trends are well presented *e.g.*, the tendency to restrict the use of the terms *Folsom* and *Yuma* to specific types of projectile points and to substitute new terms, such as *Plainview*, *Sandia*, and *San Jon*, for the variant earlier and later types. A glossary and a detailed bibliography, which includes manuscript reports, are particularly valuable from this standpoint.

In an appendix, Ernst Antevs discusses the geology of the Clovis sites in New Mexico, where classic Folsom, Plainview, and Yuma types have been found. He restates with slight modification his earlier correlation of the Clovis sites with the Estancia Pluvial, a correlation to which some geologists have objected.

IRVING ROUSE

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American Journal of Science

AUGUST 1950

RHYTHM AND SYNCHRONISM OF TECTONIC MOVEMENTS

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ABSTRACT. Stille's results concerning the time relations of tectonic movements and their "world-wide" occurrence were subjected to a severe criticism in two recent papers, one by Gilluly, the other by Rutten.

Gilluly sees only the deficiencies of Stille's system and throws it overboard entirely, thus denying its outstanding qualities. In the opinion of the present author the golden mean lies between Stille's and Gilluly's conclusions. He agrees with Rutten's criticism and conclusions in nearly every respect, and he mentions some additional evidence in support of the concept of the rhythmic alternation of orogenic and non-orogenic periods.

Stille's book on comparative tectonics, published in 1924, represents a landmark in our knowledge of the time-relations of tectonic movements. Two principles are at the base of his critical study, viz. (a) a high precision of stratigraphic dating of unconformities and non-conformities, (b) a comparative study of data collected from all available sources the world over.

Although these basic principles are entirely sound, the nature of the assembled evidence needs careful and critical examination in order to formulate reliable conclusions.

According to Gilluly and Rutten this is not the case. Their recent papers contain severe criticism on two principal aspects of Stille's work, viz. (a) on the subjective, or even prejudicial character of several cases of non-conformity timing, (b) on the heterogeneity of the assembled material and its interpretation.

However, Gilluly's conclusion, which runs as follows: "World-wide orogenic revolutions do not appear to me to have been demonstrated" is too extreme.

Rutten's opinion is more moderate and I agree with his criticisms and conclusions in nearly every respect.

The golden mean lies between Stille's and Gilluly's conclusions. Stille, in his enthusiasm for dating and parallelisation of tectonic movements, undoubtedly overshoots the mark. Gilluly, on the other hand, sees only the deficiencies of the sys-

tem and throws it overboard entirely, thus denying its outstanding qualities.

Let us remember that Bucher, in 1933, also recognized some of the deficiencies of Stille's system of orogenic epochs; yet he saw also the great merits of it. This seems to me the right attitude. For, if we want to gain some insight in the time relations of tectonic processes we must try to fix the epochs and phases of these movements as accurately as possible. Anybody who ever tried such a procedure knows how many errors may slip in, due to the nature of the paleontological and stratigraphic record. Moreover, some of the unconformities, mapped in the field, will be of local importance only. Some may even be caused by submarine downsliding and other non-tectonic processes.

It is to be expected that, with the expansion of detailed mapping, an increasing number of unconformities and non-conformities of heterogeneous origin will be found. It is well known that Stille's original list of 1924 showed 30 orogenic epochs, which increased to about 40 when he had visited North America in 1933. Gilluly published a stratigraphic column showing 44 unconformities since the Miocene reported in 60 oil-field descriptions in California.

As a necessary consequence of the nature of the movements in geosynclines and mountain chains, it is to be expected *a priori* that a great number of "epochs," "phases" and "sub-phases" of movement will turn out to have been non-contemporaneous and of only local or regional importance. As Rutten rightly pointed out, the Trondheim and Ekne phases of the Ordovician have no more than local significance at present. And as the Ardennic and Eric phases can only seldom be distinguished from each other, we should prefer to speak of Neo-Silurian or Neo-Caledonian movements. Evidently, also such subphases as the Deister, Ostenwald, and Hills of the Upper-Cimmerian epoch have only local value.

Another source of erroneous or prejudicial interpretation lies in the length of the time gap represented by some non-conformities: Suppose the youngest sediments of the folded complex A in figure 1 belong to the Lower Triassic and the unconformable sequence B belongs to the Liassic. In that case the time-gap would embrace some twenty million years in the Mid- and Upper Triassic. Both Gilluly and Rutten remark that the

time of folding of A might have taken place at any time between Lower Triassic and Liassic. However, before the deposition of B, not only folding of A took place but also denudation, possibly even peneplanation of A. If no sediments younger than A and older than B occur in the area under consideration I feel that the time of folding of A was more probably soon after the Lower Triassic than at a later time of the Triassic.

If B represents a marine transgression with direction C-D, it evidently took some time to proceed over the distance from C to D and so on. This is again a point that calls for attention.

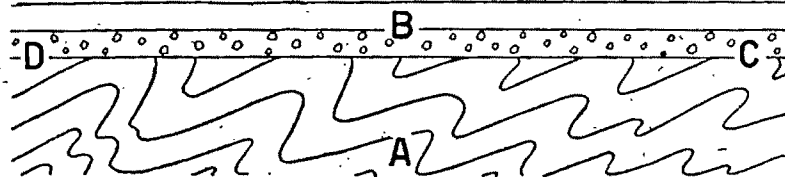


Fig. 1. Schematic representation of an angular unconformity.

However, notwithstanding these and other critical remarks, certain relatively short periods undoubtedly were characterized by folding of widely separated geosynclinal belts.

Let us recall only a few examples. Rutten admits that the Taconic epoch of movement has been established in such widely separated areas, as the Appalachians, North Ireland, South Wales, Victoria, Tasmania, Kirchizes en Tschenskij Mountains, and that the Upper Paleozoic was a period of enormous tectonic activity in the Variscian belts of five continents.

Therefore, the conclusion is justified that certain epochs of the earth's history are characterized by relatively greater tectonic unrest and stronger compression in the earth's crust than intervening periods. To this we should immediately add that even in comparatively quiet periods, like the Cambrian and Devonian, movements of minor importance have occurred. Moreover, we should avoid the term "world-wide" when speaking of the occurrence of "synchronous" or contemporaneous movements in widely separated regions. (Even the designation "contemporaneous" should be taken *cum grano salis*.) For, at the same time that strong folding occurs in a geosyncline, similar phenomena may not have taken place in a neighboring strip of the earth's crust. The special configuration of the basement may cause two geosynclines to form side

by side, one of which will be folded to an intense degree during a given epoch of compression, while the other will be hardly influenced by it. A striking illustration of this is found in the Cordilleras along the west coast of North America. The following belts are found side by side in this area: (1) the Cordilleran geosyncline, which was formed in the Pre-Cambrian and influenced by Laramide folding, (2) the geosyncline of the Sierra Nevada (Triassic and Jurassic; Nevadian folding), and (3) a geosyncline extending further west on a basement which was folded during the Nevadian revolution: the geosyncline of the Coast Ranges (Cretaceous and Lower Tertiary; Miocene folding).

The same phenomenon can be observed in the Paleozoic Wichita geosyncline of central North America. The Wichitas and Criner Hills, both of which are situated in this belt, were influenced during the Wichita and the Arbuckle epochs, but the Ardmore basin in the immediate neighborhood of the geosyncline, including the Arbuckle chains, were affected only during the latter epoch.

All available data show that the largest expanse of mountain chains since Pre-Cambrian time was occupied by the Variscides, especially toward the Upper Carboniferous (post-Sudetic and pre-Mid Permian). The second largest area has been occupied by the Alpine system since the Pleistocene. The Caledonides (Taconic and Silurian), extending over large tracts, especially in the continents of the northern hemisphere, were less extensive than the Alpine belts. The Mesozoic mountains covered the smallest areas, and surrounded particularly the Pacific. The Variscides and Alpine chains also show circum-Pacific arrangement, but these belts likewise occupied large areas in an E.W. direction, along the southern side of the northern continents.

On the other hand, however, similar epochs of movement as found in geosynclinal belts are also encountered outside these downward strips of the earth's crust. Let us only mention that the origin and rejuvenation of continental basins, as well as the time relations with regressions and transgressions, are striking phenomena. As set forth *in extenso* in "The Pulse of the Earth" all this leads to the following conclusions: (1) A correlation in time for orogenic revolutions in widely separated regions of the earth is a phenomenon, that cannot possibly be denied. (2) The simultaneous occurrence of oro-

genic movement in widely separated regions, as well as contemporaneous movements in non-orogenic areas, points to a common deep-seated cause (the character of which is still highly problematic and forms one of the fundamental problems of earth science). (3) The orogenic periods plotted against geological time show their rhythmic character as well as their time relations with other phenomena, viz. ice-ages, transgressions and regressions of epicontinental seas, formation of basins, plutonic and volcanic phenomena.

I should like to stress once more that Rutten and Gilluly were right in offering criticism of Stille's results. Yet the principles underlying Stille's method are sound and there is no excuse for throwing away the baby with the wash water, as Gilluly did.

Bucher wrote: "If orogenic deformation results from earth-wide crustal stresses, it is to be expected that the major effects are felt essentially "synchronously," that is within an interval measured by hundreds of thousands of years. The individual minor episodes, the sum of which constitutes the orogenic epoch, need not coincide in different parts of even the same orogenic belt, though they may actually do so." (Bucher 1933, pp. 415-416.)

The concept of the rhythmic occurrence of periods of increased tectonic activity is not in contradiction with uniformitarianism. In this respect I agree with Gilluly where he says: "I can see no grounds whatever for assuming any increased tempo for diastrophism during post-Lipalian time." (Gilluly, 1949, p. 590.)

Holmes is inclined to conclude that the continents must have grown progressively thicker and covered an ever-smaller area in the course of geological history. As suggested by Holmes this would involve a progressive increase in the rate of denudation and geosynclinal sedimentation as well as a progressive speeding up of orogenic processes. The theory of a conspicuous acceleration of these phenomena, representing a genuine departure from the theory of uniformitarianism, has been advocated by several authors. However, as far as can be ascertained, the major cycles of diastrophism do not display a marked speeding up of their rhythm. As a matter of fact, minor cycles, including the phases and sub-phases of Stille, show an increasing frequency when plotted on the geological

time scale; but probably this phenomenon is due to the fact that unravelling the earth's structural history becomes ever more difficult the farther we try to penetrate into the past. Moreover, one should not forget that after a period of diastrophism, when the mountain belt regains isostatic equilibrium, part of the detritus is transported to the deep sea and is forever lost from the continents. This amount should be taken into account when estimating the progressive thickening of the continents.

Recently, Lafitte argued that there are no reasons for accepting the non-uniformitarian viewpoint put forward by Cayeux. For, he clearly showed that "abnormal" sediments, as well as the alternation of orogenic and non-orogenic periods, do not conflict with the sacrosanct dogma that the present is the key to the past.

One of the most baffling problems of earth science is to find the motor of the deep-seated processes which cause a rhythmic shortening of the earth's crust and the earth's radius. A vast increase of geological and geophysical data are needed before this problem can be attacked without entering into the realm of mere speculation.

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DELFT, HOLLAND

THE STRUCTURE OF ECUADOR

VICTOR OPPENHEIM

ABSTRACT. The territory of Ecuador can be divided into three tectonic provinces: Coastal, Eastern and Central. The study of these in the light of the writer's field observations as well as the known published data show that the Western Cordillera of Ecuador, of upper Cretaceous age, preceded the rise of the later Tertiary Cordillera Real. The former is magmatic while the latter is of geosynclinal and metamorphic constitution.

The structure of the three geological provinces is of block-faulted nature. Active volcanism and persistent seismicity of the cordilleras point to the direct effects of active tectonic forces still at work in this country.

INTRODUCTION

EXTENSIVE geological field work throughout most of Ecuador was carried out by the writer in 1938 and 1939 when in charge of field work for the Anglo-Saxon Petroleum Company. Additional investigations were also made in the writer's position as Honorary State Geologist for the government of Ecuador. The writer's notes were recently revised in the light of his later geological observations in the Andean region as well as in connection with the more recent geological data released by the oil companies operating in Ecuador. For specific geological information reference will be made to the existing publications. Particular emphasis in this study is placed on the tectonic movements in Ecuador and their relation to volcanism and the high seismicity of this part of the Andes, some of the effects of which have been witnessed by the writer.

Ecuador presents an interesting field of study of the intricate relations between tectonics, volcanism and seismicity.

TECTONIC PROVINCES OF ECUADOR

Three different tectonic regions or provinces corresponding to geographical divisions of the country can be distinguished in the structure of Ecuador:

- (1) The Coastal Province, extending between the Cordillera Occidental and the Pacific Ocean.
- (2) The Eastern Province or, "Oriente," extending east of the Cordillera Real, toward the Brazilian Shield.
- (3) The Central Andean Province, embracing the high ranges of the Cordillera Real and Cordillera Occidental and the Inter-Andean Basin.

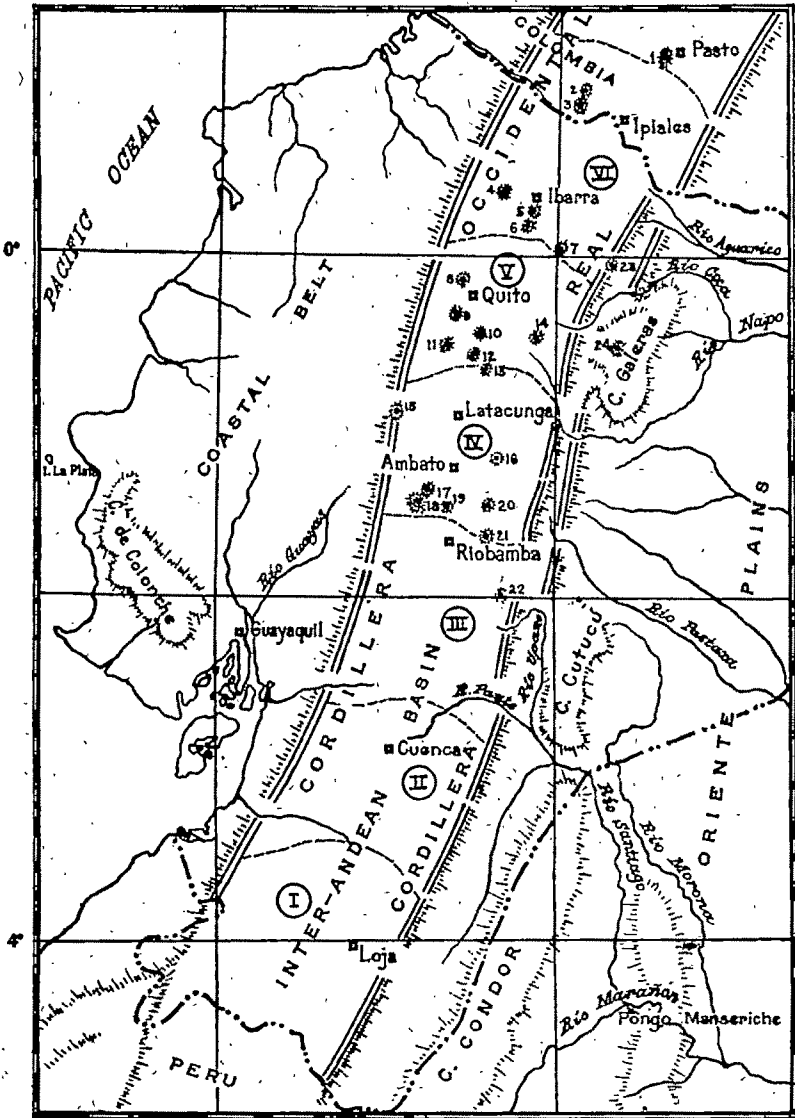
Each of these provinces shows distinct characteristics and diastrophic effects. The three are closely related, however, in

making this part of the Andes one of the very seismic and volcanic regions of the continent, tectonically still very active.

The Coastal Province.—An extensive fault at the foot of the Cordillera Occidental separates this cordillera from the coastal sedimentary belt. This fault has been described by Sheppard (1937); its southern continuation in northwestern Peru has been indicated by Iddings and Olsson (1928). To the north this fault zone continues with possible interruptions along the western foot of the Cordillera Occidental of Colombia as far north as the Choco region, where it has been observed by the writer in numerous outcrops (Oppenheim, 1949). Another great fault extends along the continental shelf from northwestern Peru; in a northerly direction, possibly as far as Manta. It passes west of the Island La Plata some fifteen miles west of the mainland of Ecuador. Although the continuation of this fault northwards and along the continental shelf of Colombia is uncertain, general faulting along the shelf in this direction could be expected. The Pacific Fault of Peru and its northern continuation appears, thus, to run parallel to the fault zone of the Cordillera Occidental. The coastal sedimentary belt, bounded by these two major faults or zones of faulting, appears in itself intensely fractured and faulted.

The sediments composing the coastal belt are Cretaceous and Tertiary strata of shallow water deposition. The Tertiary alone is about 7,000 meters thick. This would indicate a continuous subsidence of the coast throughout Cenozoic times. The rise of the western Andes, which began in Mesozoic times and continued throughout the Cenozoic, has evidently accompanied the foundering of the coastal belt and the formation of the great faults. The same forces could have also caused cross-faulting of the sedimentary belt by a number of minor fractures which trend to the northwest or from east to west. The intricate pattern of these faults is not always visible by surface observations and is best revealed in the many borings made on the coast. They indicate a complex tectonic block structure. The Eocene and Oligocene beds appear to be more intensely fractured and faulted, while the Miocene beds are much less so. This points to a lesser diastrophic activity in later Tertiary times. Folding also appears prominently in the Tertiary belt. The Sierra Colonche-Chongon is the highest range on the coast; striking in a northwesterly

STRUCTURAL SKETCH OF CENTRAL ECUADOR



VOLCANOES

78°

M. A. G. G. G. G.

- | | | |
|--------------|---------------|------------------|
| 1 Galeras | 9 Atacazo | 17 Carthuisirazo |
| 2 Cumbel | 10 Paschoa | 18 Chimborazo |
| 3 Chiles | 11 Illiniza | 19 Igualata |
| 4 Cotacachi | 12 Rumiñahui | 20 Tungurahua |
| 5 Imbabura | 13 Cotopaxi | 21 Alter |
| 6 El Mojanda | 14 Antisana | 22 Sangay |
| 7 Cayamba | 15 Quilotoa | 23 Reventador |
| 8 Pichincha | 16 C. Hermoso | 24 Sumaco |

BASINS

I Loja - II Cuenca - III Riobamba - IV Latacunga - V Quito - VI Ibarra-Ipiales

— Andean fault zones

direction, it seems independent of the Western Cordillera, but its core of igneous rocks suggests the possibility of its being a spur of the Western Andean batholith.

Numerous igneous intrusions in the form of dikes and sills have greatly affected the southern part of the coastal belt, and particularly its Eocene and Oligocene beds. Less is known about the occurrence of intrusive bodies in the northern part of the Ecuadorian coast. They do not seem to be frequent in the sediments of the southern coast of Colombia, although igneous rocks form the foundation of the Gorgona Island off Colombia's coast. In Colombia widespread intrusions are related to the intense diastrophic movements of late Cretaceous and early Tertiary times, age of the rise of the Western Cordillera. The intrusions, as they occur in the sedimentary belt, could have preceded or followed the process of faulting.

The subsidence of the coast ceased completely at the close of Tertiary times and in the Pleistocene a distinct emergence of the Ecuadorian coast has taken place. Three levels of raised sea beaches or "tablazos" are known to extend along the coast of northern Peru and southern Ecuador. They have been described by Iddings and Olsson (1928) as well as by Sheppard (1937). Sheppard describes three levels of "tablazos" in southern Ecuador at approximately 3 meters, 80 meters and 150 meters above sea level. Along the northern coast the "tablazos" occur at considerably higher levels; on the Isla de la Plata they are known at about 30 meters, 160 meters and 250 meters respectively. The individual thickness of these raised sea beaches is of about 5 meters and their age as identified by numerous fossils (Barker, 1933) dates from early Quaternary to Recent times. This indicates that their rise must have taken place in Recent times and points to tectonic oscillations that are still taking place on the southern Ecuadorian coast. Contrary to this, the Pacific coast of Colombia shows the effects of submergence in its southern part and emergence along the Choco coast to the north. The tectonic pattern of the Colombian coastal sedimentary belt is also quite different from the Ecuadorian coastal belt. Faulting of the sedimentary strata in the former is of minor importance and the existing faults follow the trend of folding, which is generally north-south. The rise of the coastal Choco basin to the north is determined by a recent marine fauna found by the writer west of Quibdó at about 80 meters above the present sea level.

The Eastern Province.—The eastern flank of the Cordillera Real and the vast territory east of the Andes were studied by the writer (Oppenheim, 1943a), mainly in 1938 and 1939 during several expeditions in which hundreds of miles were covered on foot and in native canoes. Many of the reconnaissance observations made at this time broadened the earlier studies of Wasson and Sinclair (1927). In a recent publication Tschoopp (1948) summarizes the stratigraphic data contributed by many petroleum geologists in the service of oil companies up to 1947.

The eastern flank of the Cordillera Real consists mostly of a series of metamorphic rocks, which the writer called "Andean System"; it drops abruptly from elevations of over 4,000 meters to the plains of the "Oriente," at about 500 meters above sea level. An extensive major fault bearing evidence of a widespread zone of fracturing and tectonic crushing extends along the eastern foot of the cordillera from the southern to the northern boundary of Ecuador. It continues farther into Colombia east of the village of San Francisco. Higher up the flank of the cordillera and to the west, several other large longitudinal faults have been recorded. The largest of these begins south of the valley of Rio Pastaza and continues past Topo and Baeza to Cerro Tigre on the Colombian border. This great fault marks a belt of tectonic depression and intense crustal deformation. At the southern end of this zone of faulting, and somewhat to the west, lies the active volcano Sangay (5,328 meters), while near its northern end and on the line of the equator, is situated another recently active volcano, Reventador (1,622 meters). The presence of these active volcanoes in this zone of tectonic weakness points to its persisting structural instability. A large granodioritic batholith extends to the east of the fault zone from the Pastaza Valley to the Valley of Rio Quijos. Similar granodioritic intrusions have been noticed in the same zone north of Reventador. The lavas of Reventador as well as Sangay are, however, of an unusual alkaline, nephelinic composition of a distinctly Atlantic type (Colony and Sinclair, 1928). The great fault zone at the foot of the Cordillera Real appears exposed in many sections; however, in parts of its northern extension the contact is covered by considerable thicknesses of "mesa" formations. Where exposed, the fault seems to be of a normal type, but

with local thrusting to the east. The orogenic forces were evidently directed almost vertically but a component from the west.

Rising above the "Oriente" plains, east of the Cordillera Real and between lat. $1^{\circ} 45'$ and 3° S., extends the Cordillera de Cutucu, explored by the writer in 1938 (Oppenheim, 1943a). It is a continuation of the Cordillera del Condor and the Cordillera Oriental of Peru. It appears extremely faulted and fractured along its western flank, where it is separated from the Cordillera Real by the synclinal depression of Rio Upano. A great number of igneous intrusions of different ages have affected this sedimentary range. The southern part of the Sierra de Cutucu appears divided; its eastern branch extends east of the Santiago River and crosses the Pongo de Manseriche where it joins the Cordillera Oriental of Peru. The western branch of the Cutucu mountains, as stated, forms the Cordillera del Condor. To the north the Sierra de Cutucu plunges under the Valley of Pastaza, reappearing as the Galera Mountains north of the Napo River. The volcano, Sumaco (3,190 meters) is the highest peak of this range. To the north the Galera Mountains flatten and disappear in the valley of Rio Coca and Aguarico. The western flank of the Galera Mountains, although largely covered by the volcanic ejectamenta of Sumaco, appears to be intensely fractured and faulted. The Cordillera Oriental of Colombia has, thus, no connections with the eastern ranges of Ecuador.

The eastern flanks of the Cordillera de Cutucu as well as the Galera Mountains expose a gentle eastern slope. The Oriente plains extending for great distances to the east towards the Brazilian shield, are folded into several large and successive anticlinal folds, striking in a north-south direction and gradually flattening to the east.

Several diastrophic phases have affected the complex tectonic history of the "Oriente" province (Tschopp, 1948). The earliest diastrophism is evident in the lower Paleozoic Gualaquiza Series of an apparently Caledonian cycle followed by volcanic activity in the later Paleozoic times. During the early Mesozoic the volcanism was accompanied by intense erosion and later continental sedimentation. The north-south trend of the tectogenesis has already been clearly outlined. During the late Mesozoic the rise of the geosyncline bordering the Cordillera

Real began to accentuate, and finally, in late Cenozoic, the last great diastrophic movement took place in the "Oriente" province, causing the final rise of the Cutucu and Galera Ranges and resulting in the folding of the young Tertiary "Oriente formation." This last cycle has brought about the intense faulting of the eastern flank of the Cordillera Real as well, probably, as the rise of the volcano Sumaco.

Tectonic activity along the eastern flanks of the Cordillera Real and at the eastern foot of the same cordillera is still in progress, as far as can be judged by the many "mesa" levels representing former river valleys that were raised several hundred meters in the process of recent tectonic uplifts.

The Central Andean Province.—As we have seen in the preceding outline, the Andean massive is bounded by great fault zones to the east and west. It rises abruptly above the Coastal and "Oriente" plains of a few hundred meters in elevation, to the great height of the Inter-Andean plateau at about 3,000 meters, above which rise the two rows of Ecuador's volcanic peaks which surmount the Cordillera Occidental and Cordillera Real. The base of the whole Andean range is in places only 100 kilometers wide, while its width in the upper part is about 60 kilometers. The highest peak of the Western Cordillera is the volcano Chimborazo (6,810 meters), while the highest peak in the Cordillera Real is the volcano Cotopaxi (5,948 meters). The comparatively narrow and elongated Inter-Andean basin separating the two cordilleras is largely filled with great masses of volcanic debris, tuffs and lavas. Thus, the contact between the two cordillera massives is completely obscured. Judging by the sharp differences in the rock composition of the two cordilleras, extensive zones of faulting and fracturing must exist along the inner base of the cordilleras facing the basin. These fault zones to the east and west of the basin outline the block structure of the Inter-Andean basin. This basin extends from south of Loja northwards and across the northern boundary of Ecuador into Colombia, where it may find its tectonic closure at the Pasto uplift. As previously stated, the great amount of pyroclastic materials and igneous flows obscure the intricate structure of this Inter-Andean basin. However, a physiographic study which has significant bearings on its structure indicates that the basin can be divided into a number of distinctly separate blocks, individually outlined by trans-

verse ranges or groups of volcanic cones. Thus, we have from south to north the Loja Basin, the Cuenca Basin, the Riobamba Basin, the Latacunga Basin, the Quito Basin and the Ibarra-Ipiales Basin. These inner basins form a block structure pattern. The Loja, Cuenca and Latacunga basins consist of Miocene or Pliocene continental sediments, several hundred meters in thickness. The sediments are intensely faulted and fractured and in the case of the Cuenca Basin also compressed into several folds. The northern basins are separated from each other by centrally located volcanoes or groups of volcanoes. The volcano Igualata (4,452 meters) separates the Riobamba and Latacunga basins; the volcanoes Pasachoa (4,255 meters) and Ruminahui (4,767 meters) limit the latter from the Quito Basin; the volcanoes Imbabura (4,382 meters) and Mojanda (4,280 meters) separate the Quito Basin from the Ibarra-Ipiales Basin. The latter is closed to the north by the volcano Galeras and the Pasto batholith of southern Colombia. The great Cauca depression between the Cordillera Occidental and Central of Colombia could be interpreted as a northern structural continuation of the Inter-Andean basin of Ecuador into Colombia. The Western Cordillera of Ecuador continues as the Cordillera Occidental of Colombia, where it is, however, considerably lower. The Cordillera Real of Ecuador continues throughout Colombia as the Cordillera Central. The Cordillera Oriental of Colombia forms a distinct branch of the Central Cordillera at about lat. 2° N. (Oppenheim, 1949). It bears no direct relation with any of the Ecuadorian ranges.

The Inter-Andean Basin of Ecuador suggests a similarity with the central Inter-Andean plateau of Bolivia. Both are wedged between high Andean massives situated along the edges of the main continental curvatures. However, while the Ecuadorian Inter-Andean block is placed on the outward bend to the northeast, the Bolivian Inter-Andean Basin (Oppenheim, 1947), the Puna block, is situated on an inward N.W. bend of the Andes. This position may partly account for the intense and complex tectonism of these two distant regions of the Andes. However, in Bolivia volcanism has ceased, while the orogenesis as shown by the rising "mesas" still continues (Oppenheim, 1943b). In Ecuador both factors are present and continue in an active stage.

The Cordillera Real consists mainly of metamorphic rocks such as gneiss, micaschists, and phyllites, with acid intrusives. The age of these rocks is uncertain and it may range from Pre-Cambrian to Paleozoic. It is evidently of a geosynclinal origin; hence the intense metamorphism of its composing elements.

The Western Cordillera is built mainly of great masses of pyroclastic materials and lavas of porphyritic nature. Diabase and granodioritic batholiths also appear in this cordillera. The extensive occurrence of recently described (Thalman, 1943) Upper Cretaceous sediments along the western flank of the cordillera indicates the age of this cordillera as uppermost Cretaceous. Its complex inner structure is little known. The absence, however, of crystalline formations (Tschopp, 1948) so typical in the Cordillera Real, clearly shows a different origin. The Western Cordillera rose in the late Cretaceous times, whereas the Cordillera Real reached its maximum growth at the close of Tertiary times (Oppenheim, 1947). The younger age of the Cordillera Real is indicated by the several historically active volcanoes, some of which continue to be active or to have been active recently (Cotopaxi, Tungurahua, Sangay, Sumaco and Reventador). Evidence of the continuous rise in Pleistocene times of the Cordillera Real can also be found, as stated, in the many "mesa" levels along the eastern flank of the cordillera.

Geophysical Data.—The results of gravity observations carried out by the oil companies operating in Ecuador have not been made public; however, judging from the data given by Tschopp (1948) as well as by O. F. Sundt (personal communication in 1945), it is evident that the eastern Andean range corresponds to a zone of typical geosynclinal conditions, showing minimum gravity. Thus, the gravity anomalies have a minimum near Latacunga of -201 mgl. Bouguer and -148 mgl. to the east, still in the Andean region at the confluence of the rivers Patate and Chambo, indicating a rise of gravity to the east. At the foot of the Cordillera Real at Mera the gravity rises to -148 mgl. Farther to the east across the "Oriente," the rise of the gravity anomalies is persistent and reaches at Tarqui, on the border with Peru, a maximum of $+14$ mgl. Bouguer. The rise of the gravity from the Andes eastwards reflects a mass deficiency under the Andes, and is

also due to the increasing nearness of the basement shield-rocks that underlie the sedimentary formations and culminate with the Brazilian Shield proper, east of the "Oriente." The rise of the anomalies east of the Andes is not uniform, and the many maxima observed in the reading correspond to geological structures, particularly anticlinal folds, in the sedimentary cover. Some of the maxima, however, reflect the presence of heavy masses in the deepseated basement underlying the sedimentary cover.

VOLCANISM AND SEISMICITY

The tectonic outline of Ecuador as one of the intensely fractured and faulted regions of the Andes finds its expected confirmation in the still-persistent seismicity marked by its many destructive earthquakes throughout historical times, as well as by the great number of active or latent volcanoes, one of which, namely Sangay, is one of the most active in the world. Although the relation of the deepseated causes of the continuous earthquakes and the past and present volcanic activity will necessarily remain obscure due to the impossibility of direct observations, it is evident that tectogenesis may cause seismicity and under certain conditions of crustal weakness may result in volcanic outbreaks.

Analyzing the volcanic activity in the Ecuadorian Andes, we find that within a narrow belt between lat. 2° S. and lat. 1° N. there are twenty-five volcanoes that show clearly preserved craters with comparatively recent lava flows; six of the volcanoes have been repeatedly active within the memory of man since the 16th century (Wolf, 1892). Of the twelve volcanoes of the Western Cordillera only the volcano Pichincha (4,777 meters) has been active in historical times (Sauer, 1943). Outstanding eruptions of Pichincha have been recorded in 1566, 1575 and 1582. The volcano was then quiet for seventy-eight years, until 1660 when a very strong eruption took place. The later, smaller eruptions of Pichincha were recorded in 1830 and 1881. The volcano has not been active since; however, judging by its past long intervals between eruptions, it cannot be considered as extinguished. The frequent minor local earthquakes in the area of Quito, which lies at the foot of Pichincha, undoubtedly bear relation to the inner activity of this volcano.

Reviewing briefly the volcanoes in the area of the Cordillera Real, we find that of thirteen outstanding volcanic cones, five have been active in historical times. The volcano Antisana (5,756 meters) had eruptions recorded in 1590, 1728, and 1801. Fresh lava flows have been observed at the western foot, probably of an eruption in 1871. The volcano Cotopaxi (5,943 meters) was first recorded in eruption in 1534; then it was very active from 1742 to 1768, after which it was quiet for thirty-five years until 1803. It was further intermittently active between 1845 and 1880. The volcano Tungurahua (5,087 meters) had its activity recorded during the following years: 1641, and intermittent eruptions between 1773 and 1781; a very strong and last eruption took place in 1886. The volcano Sangay (5,323 meters), the southernmost volcano of the Cordillera Real, has been in constant eruption, with undiminishing lava flows, during all historical times. It is one of the most active volcanoes known. Much less has been recorded about the two volcanoes east of the Cordillera Real; Sumaco was apparently active between 1865 and 1925 and Reventador was active in 1926. It is noteworthy to mention that the volcano Puracé (Oppenheim, 1950), in the Central Cordillera of Colombia, lies on the northern extension of the Ecuadorian volcanic range and is still active, although much less so than Sangay at the southernmost end of the range.

The above outline of the historic activity of the Ecuadorian volcanoes indicates that while volcanic activity in the Western Cordillera has almost ceased, it is still in an active stage in the eastern cordilleras of Ecuador.

Wolf (1892) describes twenty-four recorded earthquakes between 1541 and 1868, many of which repeatedly destroyed the largest cities of Ecuador, such as Quito, Ibarra, Ambato and Riobamba, causing many thousands of casualties in each locality.

The three large and destructive recent earthquakes that took place in 1939, 1942 and 1949, evidently reflect the same causes of crustal instability that are expressed in the complex tectonic pattern and volcanism in the Andes of Ecuador.

CONCLUSIONS

The three main tectonic provinces into which Ecuador can be divided indicate large-scale block faulting as their

structural pattern. Only slight thrusting exists at the eastern foot of the Cordillera Real.

The Cordillera Occidental of predominantly volcanic and pyroclastic composition is of Upper Cretaceous age, while the eastern Cordillera Real is composed of crystalline metamorphic, probably early Paleozoic, rocks and is evidently of late Tertiary to Pleistocene age of uplift. Hence the rise of the Cordillera Occidental preceded the uplift of the typically geosynclinal ranges of the Cordillera Real and the Sierra de Cutucu.

The Central Inter-Andean basin is a block-faulted intermediary depression zone forming a link between the old Western and the more recent Eastern cordilleras. It was probably brought to its much lower elevation along with the rise of the western edge of the great eastern geosyncline, and was later covered by a considerable thickness of more recent volcanic materials. Besides the extensive fault zones that limit this inner basin to the east and west, it is also divided into large blocks by transverse fracture zones.

The volcanic activity of the Cordillera Real, very active in historic times, coupled with the persistent magmatic activity of the volcano Sangay, indicate that the tectogenic processes in the Cordillera Real are still at work. The general rise of the Ecuadorian Andes is also evident in the different levels of raised sea beaches or "tablazos" along the coast as well as in the different levels of old river valleys, "mesas," on the eastern flank of the Cordillera Real.

Thus the recurrent earthquakes, some of which have been of recent destructive effects, as well as the existing active or latent volcanism, are reflections of the forces in the process of mountain-building which is actually taking place in this part of the Andes.

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BOGOTÁ

COLOMBIA

PRESSURE—VOLUME—TEMPERATURE RELATIONS IN WATER AT ELEVATED TEMPERATURES AND PRESSURES*

GEORGE C. KENNEDY

ABSTRACT. Development of new high-temperature alloys has made possible precise measurements of P-v-T relations for water over a considerable pressure and temperature range. Much of the existing published data on P-v-T relationships at supercritical pressures and temperatures is in considerable error and new values at temperatures up to 1000°C. and pressures up to 2500 bars are herein presented.

INTRODUCTION

IN recent years as creep-resistant alloys have become available and as new and ingenious apparatus has been designed, particularly by Goranson (1931) and Tuttle (1948), the pressure and temperature range for hydrothermal experimentation has greatly increased. Consequently, accurate P-v-T data for water are needed for the new range.

P-v-T relations in water for the temperature range 0°C.-460°C. and the pressure range 0-350 atmospheres have been investigated with extreme precision and reported upon in papers by Smith and Keyes (1934), and Keyes, Smith and Gerry (1936). The equation of state derived by these workers from research in this temperature-pressure region has been used to predict the P-v-T relations to 871°C. (1600°F.) and 380 bars (5500 p.s.i.). Agreement between the experimentally determined values in the 800°C. region reported upon in this paper and the calculated values as presented by Keenan and Keyes (1936) reveals the accuracy and applicability of their equation of state, derived from the work below 460°C.

Previous reconnaissance measurements of P-v-T relationships for water at high temperatures and pressures have been made by Goranson (1938). Goranson's data and those presented in this paper are not in good agreement. The reasons for this will be discussed later. Measurements have also been made by Van Nieuwenburg and Blumendal (1932) and by Tammann and Ruhénbeck (1932). The results of these workers have been discussed by Goranson (1938).

* Paper No. 113 published under the auspices of the Committee on Experimental Geology and Geophysics and the Division of Geological Sciences at Harvard University.

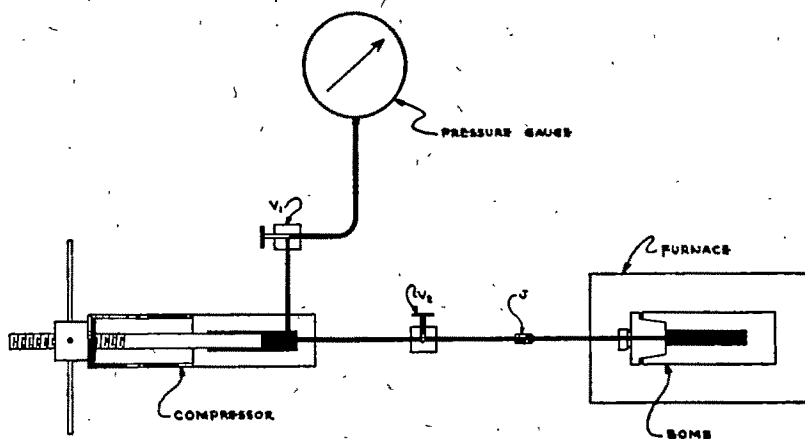


FIGURE 1.
SCHEMATIC DIAGRAM OF APPARATUS

APPARATUS AND TECHNIQUE

A diagrammatic sketch of the apparatus is shown in figure 1.

The compressor.—The compressor is the same one used and described by Benedict (1939) and similar in principle to those described by Keyes (1933). The piston diameter is $\frac{1}{2}$ inch, effective stroke 6.7 inches and displacement 21.6 cc. approximately. The driving nut has a pitch of 10 threads per inch and its position can be determined to 0.001 turn, so that a volume change of 0.0003 cc. can be estimated. The compressor was calibrated by loading it with distilled water, closing valve V_2 and advancing the piston until gauge showed some given pressure, for instance, 100 bars. The position of the compressor driving nut was then read. Valve V_2 was then opened and a portion of the water expelled from the gauge by advancing the piston. The expelled water was carefully collected at J. Valve V_2 was then closed and the piston advanced until the gauge again read 100 bars. From the positions of the nut at the start and at the end of the calibration run and the weight of the water expelled, the grams of water expelled per turn at 100 bars internal compressor pressure was immediately obtained. The calibration was repeated for 200 atmospheres, etc., so that a plot of grams H_2O expelled per turn was

obtained. This was linear with pressure to within 0.001 gm. per turn.

In the actual P-v-T determinations, the amount of water required to raise the pressure in the bomb from one volume to another was determined by much the same technique. The pressure was first raised in the compressor and on the gauge by closing valve V_2 and advancing the piston until some desired new pressure was reached. Then the valve V_2 was opened and the piston advanced, water was injected into the bomb until the new pressure was reached. The difference between the two piston nut settings, with the appropriate multiplication factor of the grams per turn at the pressure involved, gave the amount of water injected into the bomb. This method had the advantage of eliminating such corrections as the amount of water required by the gauge in going from one pressure setting to another, and also, of eliminating corrections for pressure distortion of the compressor.

Bomb. — Several innovations in bomb design and material were required to work at the maximum temperatures and pressures. Professor Nicholas T. Grant of Massachusetts Institute of Technology recommended and prepared for the writer an alloy of unusual composition and properties. The alloy is of the following composition:

Fe	23%
C	1
Ni	30
Cr	20
Co	20
Mo	3
W	2
Cb	1

The alloy is machinable and has high tensile strength at high temperatures. It permits the investigation of ranges of temperature and pressure considerably beyond those at which ordinary "stainless" steels are usable. It also has high resistance to corrosion.

Bombs of four different volumes were used, depending upon the pressure-temperature range involved. The volumes were 104.44, 41.64, 30.71 and 20.64 cc., measured under the "standard" conditions of 100 atmospheres pressure and 200°C. after being subjected to a preliminary stretching at high pressures

to test the tightness of the seal and to seat the closure piece in its copper packing.

The general design of the bombs is shown in figure 2. Experience has shown that most bomb failure was due to damage of the threads where the nut forces the packing around the bomb closure piece. A heavy tapered pipe thread, eight threads to the inch with a taper of two inches per foot, eliminated much of the trouble. The bomb can be quickly disassembled even if the tendency for the threads to weld together at the high temperatures is great, for a partial turn of the nut immediately frees all of the threads. A driving washer, of the same alloy as the bomb and nut, is provided which fits into

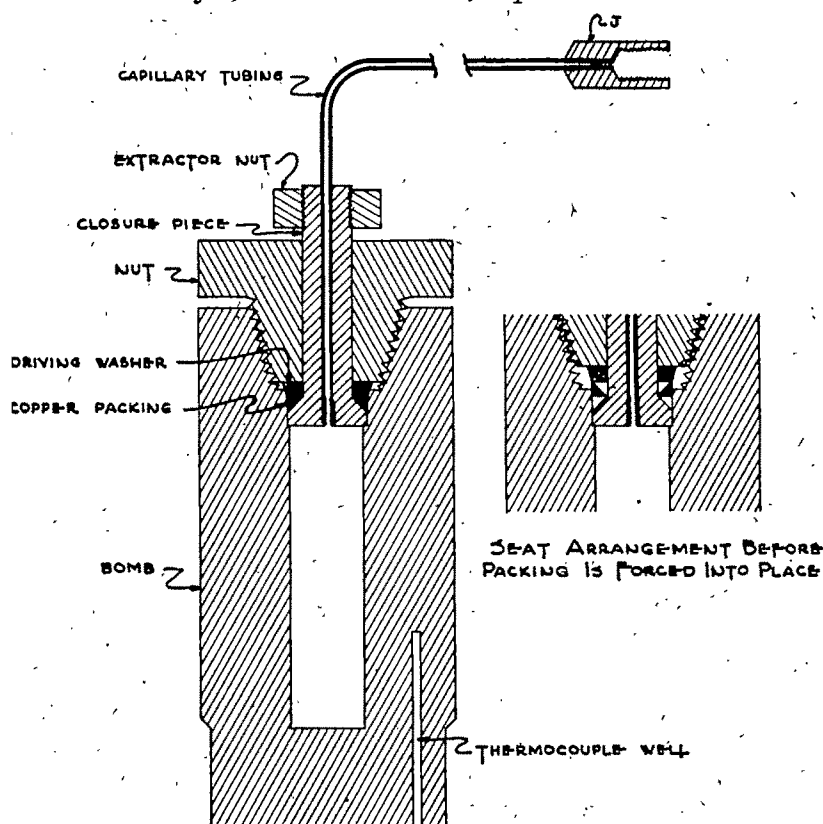


FIGURE 2.
HIGH-PRESSURE BOMB USED FOR
HYDROTHERMAL EXPERIMENTATION

a tapered seat. If the seat for the washer has parallel sides the washer tends to become barrel-shaped and will key firmly in place at the higher pressures involved. Packing is of the unsupported area type, where the pressure on the packing is automatically maintained above that inside the bomb. Annealed copper washers were used for packing. The copper washers were deformed into place to insure a tight seal. Each washer could be used several times; the washer is merely inverted for each new run. Figure 2 shows the bomb assembled after the copper packing has been forced into place and the bomb seat arrangement before the packing is forced into place.

The closure piece is drilled and fitted with a length of stainless steel capillary tubing of .10" outside diameter and of .018" inside diameter. The tubing is threaded into the head of the closure piece and silver soldered. The silver-soldered connection works well up to temperatures of about 700°C., but above this temperature is unsatisfactory. Various attempts were made at welding the capillary tubing in place so that no leak could take place around the threads, but they were invariably unsuccessful as in each case the capillary hole in the tubing closed before the weld could be completed. The solution to the problem proved simple. The capillary tubing is threaded in place and the assemblage closure piece is brought to a red heat. A well-pointed center punch is then placed with the point in the capillary hole and given a sharp blow. The capillary tubing is flared outward and a tight seal made. A connector is threaded on the other end of the capillary tubing, through which a joint can be made to a valve block and the compressor.

Temperature control and measurement.—The bomb was placed in a furnace of 3 inches inside diameter and 24 inches length. Both ends of the furnace were then stuffed with asbestos fiber and magnesium oxide brick. Exploration with a thermocouple at a temperature of 500°C. showed a temperature difference within the bomb of about two degrees. This lack of uniformity was determined without the water charge, driving nut or closure piece to the bomb in place. Under the conditions of the experiment the temperature inhomogeneity at 500°C. was probably considerably less than 2°C.

The furnace was thermostatted by means of an alternating

1937, pp. 252-254). Temperature regulation to within 0.5°C . was obtained.

Temperatures were measured by determining the e.m.f. of a 90%-platinum 10%-rhodium thermocouple calibrated against the boiling points of water and sulphur and the melting points of antimony, sodium chloride, copper and gold. The maximum deviation of the various thermocouples from Adams' tables relating e.m.f. and temperatures was 1.6°C . Each calibration temperature was known to 0.1°C . and the correction curve prepared for each thermocouple was probably nowhere in error by more than 0.2°C .

The largest error in the temperature measurements was most certainly that due to temperature inhomogeneity in the bomb. This error is very difficult to estimate and is, indeed, the largest source of uncertainty in the final P-v-T values. At the lower temperatures it is probable that the temperature measurements are correct to within less than 1°C . However, at 1000°C . the temperature uncertainty is probably of the order of 2°C . and may be somewhat more.

Pressure measurement. — A series of gauges was used for the pressure measurements. The range from 100 bars to 1400 bars was covered by two superior Heise 15-inch Bourdon gauges, manufactured by the Heise Bourdon Tube Company of Newtown, Connecticut. One of these operated to 500 bars and the other to 1400 bars. The gauges were calibrated by the manufacturer against a dead weight piston gauge. The gauge of the lower range had no correction to 500 bars; it was graduated at $\frac{1}{2}$ bar intervals and had a maximum hysteresis of less than one scale division. The 1400-bar gauge had a correction at 1400 bars of 1.5 bars with no correction at 1300 bars or below. This gauge was graduated in 2-bar intervals and had a maximum hysteresis of $1\frac{1}{4}$ scale divisions. Pressures above 1400 bars were determined by measuring the change in resistance with pressure of a manganin coil surrounded by toluene in a copper sylphon. The sylphon is enclosed in a steel cartridge which may be directly substituted for the Bourdon gauge. By this arrangement pressure could be measured with an accuracy of 5 bars. Thanks are owed to Professor Francis Birch of Harvard University, who designed the manganin coil gauge and assembly and kindly lent it to the writer. The maximum uncertainty in pressure ranges, then,

from $\frac{1}{2}$ bar in the region below 500 bars to 5 bars in the pressure region above 1400 bars.

EXPERIMENTAL METHOD

The experimental method was that of injecting a known quantity of water through a capillary tubing into a thermostatted bomb. In practice it was found convenient to thermostat the bomb at some temperature and inject water until some high pressure was built up. The piston was then backed off and the difference in piston settings gave the volume removed in going from one pressure to another. Distortion and volume changes of apparatus outside the furnace were accounted for by the method described in the calibration of the compressor. The volume of the capillary tube extending from valve block V_2 to the bomb was 0.083 cc. and corrections for this were made. The volumes of the various bombs used were determined at 200°C. and 100 bars by use of the Keyes value for water, 0.87085 gm./cm.³ and the number of grams injected by the compressor to bring the bomb to this pressure. The entire mass of data, therefore, hinges upon the correctness of this value. The volumes of the bombs were checked repeatedly throughout the experiments and runs were terminated at the pressure and temperature limits where distortion became appreciable.

Corrections were made for changes in volume of the bomb due to thermal expansion and elastic stretch. Both of these corrections were computed from thermal expansion data and from the elastic constants for the metal of the bomb, kindly supplied by Professor Grant.

Data on the coefficient of linear thermal expansion were available for the particular alloy used in construction of the bomb up to 980°C. and were extrapolated to 1000°C. At this temperature the volume correction due to thermal expansion from 0°C. was $5.18 \pm .02\%$ of the total volume of the bomb.

The volume corrections due to pressure distortion were calculated from approximate values of Young's modulus and Poisson's ratio for the alloy. The temperature coefficient for these values was unknown but should not greatly affect the final results, as the maximum correction for any of the bombs amounted to only 0.11% volume increase per 1000 bars pressure.

EXPERIMENTAL RESULTS

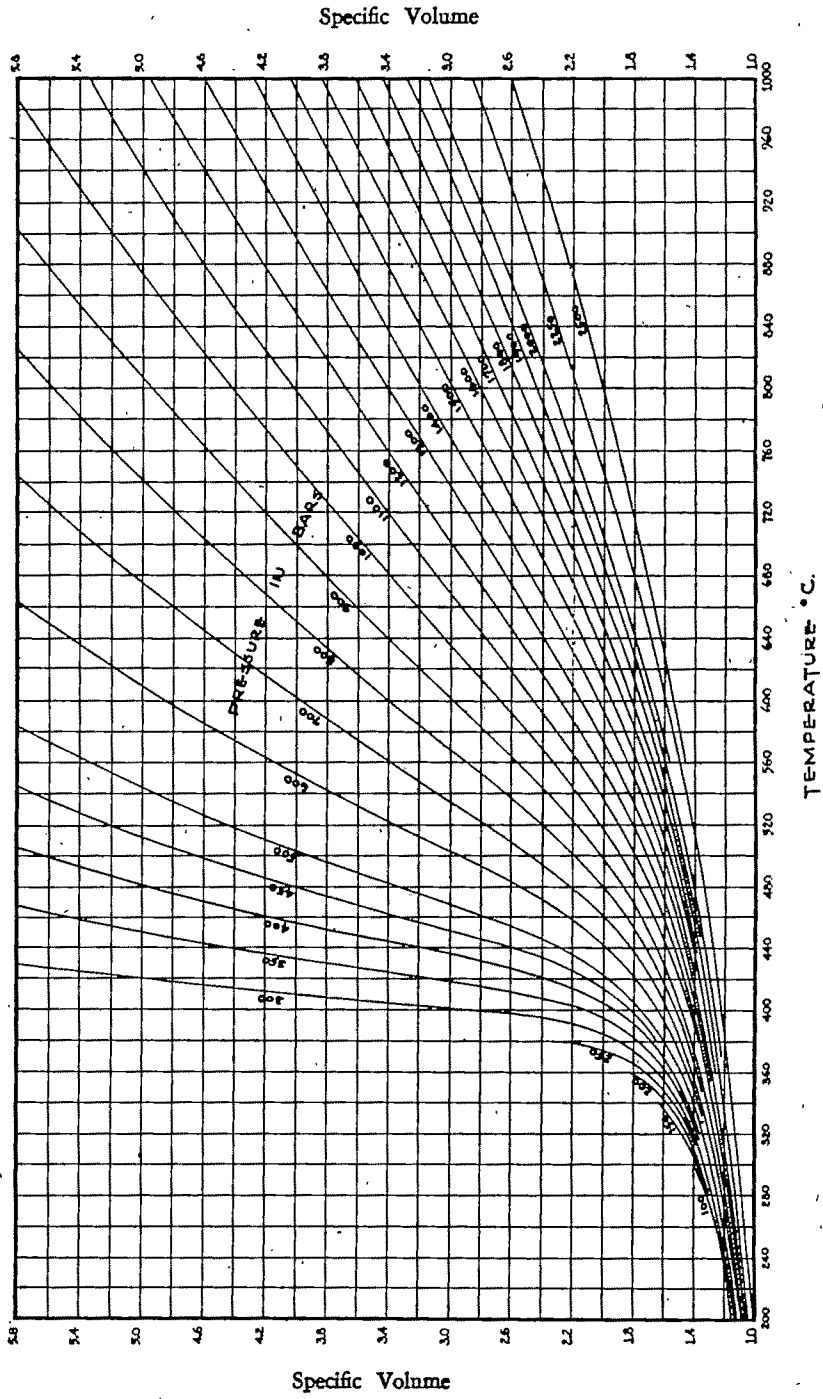
Two sets of tables are presented here. One set shows the specific volumes of water from 200°C. to 1000°C. and from 100 to 2500 bars pressure. The second set of tables shows the density of water over the same pressure and temperature intervals. Isobaric and isovolumetric curves are shown in figures 3 and 4.

The actual experimental work upon which the tables were based covered the interval of 200°C. to 600°C. at pressures up to 2500 bars. The interval 600°C. to 900°C. was covered for the pressure range 100 to 1400 bars and the interval 900°C. to 1000°C. was explored for the range 100 to 800 bars. The upper working limit in each case was that pressure at which permanent deformation of the apparatus took place at a sufficiently appreciable rate to make precise volume measurements impossible.

The tables at temperatures above 600°C. have been extended to pressures somewhat beyond the range of experimental measurements. The extrapolation has been based on the constancy of the value of $\frac{(\partial P)}{(\partial T)_v}$ at the elevated temperatures and pressures involved and is believed to be of a high order of accuracy.

The values entered in the lower temperature and pressure portion of the tables, those up to 460°C. and 350 bars, have been taken from the published data of Keyes and his collaborators. Throughout the larger portion of this range the writer's data agreed with that of Keyes to four significant figures. The agreement is much less perfect in the region near the critical temperature and pressure where measurements are difficult because the thermodynamic derivatives undergo large changes for only slight changes in T , P , or v . The uncertainties in temperature and pressure measurements seem likely to be larger in the writer's set of data than in the data by Keyes; consequently, Keyes' results have been entered for this region.

As is to be expected, the accuracy of the data presented is not uniform throughout the tables. The errors from uncertainties in the amount of water injected by the compressor and from error in determining the volume of the bomb amount to about 0.00003 gm./cc. in the final result. Those errors due to uncertainties in temperature measurement are considerably



greater. A temperature error of $1^{\circ}\text{C}.$ will introduce an error of about .001 gm./cc. at $200^{\circ}\text{C}.$ and 100 bars, but will introduce an error of only .00001 gm./cc. at $1000^{\circ}\text{C}.$ and 100 bars. Near the critical region, where derivatives are changing rapidly, an error of $1^{\circ}\text{C}.$ will introduce an error in the final density

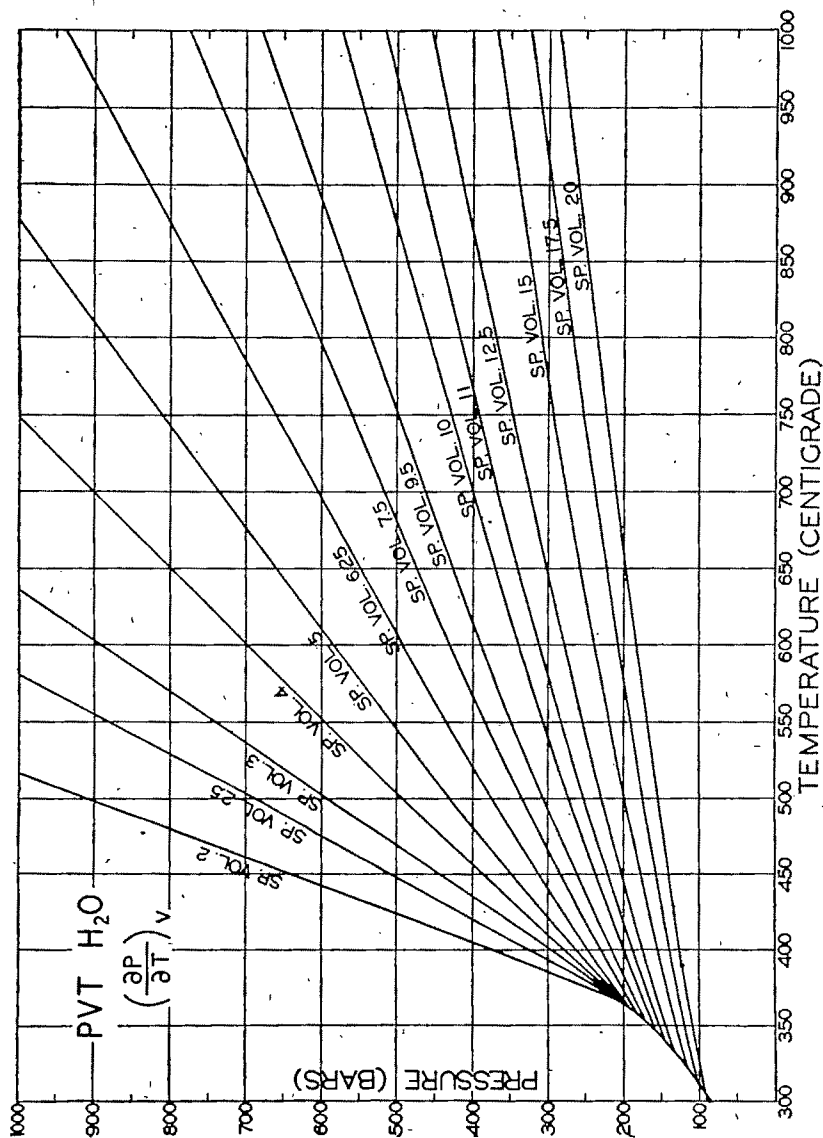


Figure 4. Isovolumetric curves for water.

result of more than .01 gm./cc. It is therefore manifestly impossible to indicate any average error for the tables. Throughout most of the table the results are computed to one more than the last significant figure. The uncertainties in the temperature and pressure measurements have been discussed in previous sections of the paper and it is believed that the density and specific volume figures are correct to within these limits.

The only previous body of P-v-T data for water at high temperatures and pressures is that of Goranson (1938). Goranson's method involved rupture of platinum capsules when steam pressure in them exceed an external nitrogen pressure. P-v-T relations were derived from knowledge of the initial amount of water placed in the capsules, with the assumptions that the platinum capsules had low or essentially zero strength and that the shape and stretch of the crucible at the time of rupture were retained so that the volume capacity of the capsule could be ascertained after removal from the bomb. It seems likely that such assumptions might prove unreliable. The agreement between the present set of data and Goranson's data is not good. However, the absolute values of the two sets of measurements at the highest temperatures are in better agreement than are the thermodynamic derivatives. The trends of the two sets of data are divergent at the highest temperatures and pressures.

Certain internal evidence appears in Goranson's data which suggests that they might be in error. Deviations from the ideal gas law, $Pv = nRT$, result largely from mutual attractions or repulsions between the gas molecules and from the volume of the gas molecules—the ideal equation implies zero volume for the gas molecules. These deviations are accounted for in a Van der Waals gas by the constants a and b . As temperature increases in even a non-ideal gas at constant pressure the v term becomes larger and the gas will behave more and more like an ideal gas. Goranson's results, however, show increasing deviations from ideality as the temperature is increased, rather than an approach to ideality.

The work of Keenan and Keyes shows that the value of $\frac{(\partial P)}{(\partial T)_v}$ is a constant where v is the critical volume,

3.1975 cm.³/gm. At values of v larger than the critical volume, $\left(\frac{\partial P}{\partial T}\right)_v$ has a slight negative temperature coefficient in the neighborhood of liquid-vapor saturation curve but rapidly approaches a constant value as the temperature of saturation is exceeded. For values of v smaller than the critical value, $\left(\frac{\partial P}{\partial T}\right)_v$ has a slight positive temperature coefficient but again rapidly approaches constancy at pressures and temperatures above those of the two-phase boundary. The value of this derivative, in the region between 600°C. and 1000°C., showed no systematic deviation from constancy for all values of v determined in this investigation. At once a means is afforded for extrapolating data from the present measurements into higher regions of T and P with reasonable assurance of accuracy. Furthermore, it seems probable that all gases should show an essentially constant value for $\left(\frac{\partial P}{\partial T}\right)_v$ for any v except when close to the saturation curve, and a plot of this derivative may afford a ready check of consistency within any body of P - v - T data. It is likewise apparent that plots of P versus T at constant v for a series of v values near the critical volume should show essentially straight lines that intersect approximately at the critical temperature and pressure, because at the critical temperature widely ranging specific volumes show essentially the same pressure (see fig. 4). The value of $\left(\frac{\partial P}{\partial T}\right)_v$ has been evaluated from Goranson's data for specific volumes ranging from 2.3 to 3.5. The value is constant for any v as is to be expected, but is much too large as is shown by plots of P versus T at v constant. The extrapolated straight-line plots do not intersect at approximately the critical temperature and pressure, but rather, cross the critical isobar at temperatures ranging from 470°C. to 500°C.

ACKNOWLEDGMENTS

Thanks are due to Professors Francis Birch and L. C. Graton, who critically read this manuscript and offered suggestions during the course of the experimental work. Mr. Harold Ames made much of the equipment and aided the writer in many ways.

TABLE I
Specific Volumes of Water
Pressure in Bars

Temp. °C.	100	150	200	250	300	350	400	450	500	600	700	800
210	1.14880	1.14368	1.13899	1.13490	1.13032	1.12670	1.1222		1.1145	1.1072	1.1003	1.0936
220	1.16393	1.15885	1.1537	1.14923	1.14416	1.14031	1.1358		1.1276	1.1197	1.1128	1.1052
230	1.18088	1.17514	1.16973	1.16454	1.15957	1.15479	1.1499		1.1407	1.1325	1.1245	1.1169
240	1.19903	1.19272	1.18670	1.18096	1.17548	1.17023	1.1648		1.1551	1.1460	1.1373	1.1292
250	1.21890	1.21177	1.20501	1.19862	1.19255	1.18676	1.1808		1.1702	1.1602	1.1509	1.1421
260	1.24066	1.23251	1.22488	1.21770	1.21093	1.20451	1.1979		1.1862	1.1754	1.1652	1.1558
270	1.26468	1.25525	1.24656	1.23843	1.23082	1.22367	1.2168		1.2034	1.1916	1.1806	1.1704
280	1.29147	1.28049	1.27039	1.26110	1.25246	1.24443	1.2363		1.2219	1.2089	1.1968	1.1858
290	1.32170	1.30864	1.29681	1.28604	1.27615	1.26704	1.2578		1.2418	1.2273	1.2142	1.2021
300	1.35698	1.34050	1.32638	1.31382	1.30256	1.29161	1.2816		1.2635	1.2474	1.2330	1.2198
310	1.39704	1.37713	1.35992	1.34476	1.33126	1.31912	1.3073		1.2869	1.2688	1.2528	1.2384
320	1.44636	1.42017	1.39855	1.38006	1.36382	1.34940	1.3359		1.3124	1.2919	1.2740	1.2582
330	19.39	1.47247	1.44313	1.42065	1.40064	1.38316	1.3676		1.3404	1.3171	1.2971	1.2795
340	20.42	1.53878	1.49926	1.46847	1.44308	1.42134	1.4031		1.3712	1.3444	1.3217	1.3021
350	21.47	1.63999	1.56986	1.52652	1.49307	1.46534	1.4426		1.4046	1.3735	1.3477	1.3257
360	22.46	1.61	1.66659	1.60116	1.56531	1.51986	1.4866		1.4422	1.4061	1.3765	1.3515
370	23.32	12.57	1.9235	1.6965	1.6272	1.5792	1.5448		1.4869	1.4433	1.4089	1.3803
380	24.19	13.54	7.03	1.865	1.731	1.658	1.6120	1.5720	1.5381	1.4875	1.4450	1.4125
390	24.98	14.35	8.30	2.275	1.881	1.762	1.686	1.647	1.597	1.534	1.4836	1.4460
400	25.73	15.07	9.22	4.635	2.165	1.895	1.795	1.723	1.666	1.584	1.5275	1.4802
410	26.31	15.72	9.96	6.061	2.800	2.096	1.921	1.815	1.745	1.643	1.572	1.5220
420	26.88	16.32	10.60	6.925	4.015	2.466	2.087	1.935	1.839	1.708	1.625	1.5633
430	27.48	16.88	11.17	7.600	4.962	3.103	2.338	2.088	1.952	1.783	1.685	1.6114
440	28.09	17.42	11.71	8.176	5.662	3.806	2.710	2.395	2.093	1.869	1.749	1.6602
450	28.73	17.93	12.19	8.69	6.23	4.436	3.144	2.576	2.272	1.971	1.819	1.7188
460	29.41	18.42	12.66	9.17	6.73	4.955	3.714	2.921	2.489	2.090	1.903	1.7813
470	30.04	18.90	13.11	9.60	7.18	5.425	4.163	3.297	2.750	2.228	1.992	1.8504

TABLE 1 (Continued)
Specific Volumes of Water
Pressure in Bars

Temp. °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
200	1.0872	1.0811	1.0752	1.0696	1.0642	1.0591	1.0538	1.0488	1.0408	1.0356	1.0304	1.0258	1.0131	1.0027
210	1.0984	1.0919	1.0857	1.0798	1.0742	1.0688	1.0628	1.0568	1.0501	1.0448	1.0396	1.0348	1.0219	1.0108
220	1.1096	1.1027	1.1061	1.1000	1.0940	1.0878	1.0817	1.0754	1.0696	1.0643	1.0597	1.0540	1.0410	1.0295
230	1.1214	1.1141	1.1071	1.1005	1.0942	1.0882	1.0818	1.0753	1.0695	1.0645	1.0596	1.0539	1.0408	1.0292
240	1.1339	1.1261	1.1187	1.1117	1.1051	1.0988	1.0920	1.0860	1.0799	1.0743	1.0692	1.0639	1.0491	1.0370
250	1.1470	1.1386	1.1307	1.1233	1.1162	1.1096	1.1033	1.0968	1.0901	1.0848	1.0786	1.0727	1.0590	1.0462
260	1.1609	1.1520	1.1435	1.1356	1.1281	1.1211	1.1141	1.1069	1.1012	1.0954	1.0899	1.0838	1.0696	1.0558
270	1.1755	1.1659	1.1569	1.1484	1.1404	1.1329	1.1260	1.1196	1.1128	1.1061	1.0996	1.0929	1.0786	1.0651
280	1.1911	1.1807	1.1710	1.1620	1.1534	1.1454	1.1380	1.1312	1.1239	1.1174	1.1108	1.1036	1.0889	1.0748
290	1.2079	1.1966	1.1862	1.1764	1.1672	1.1587	1.1506	1.1432	1.1358	1.1289	1.1219	1.1144	1.0995	1.0846
300	1.2253	1.2131	1.2019	1.1913	1.1815	1.1724	1.1639	1.1559	1.1480	1.1407	1.1334	1.1257	1.1100	1.0946
310	1.2438	1.2305	1.2183	1.2069	1.1964	1.1866	1.1772	1.1687	1.1604	1.1530	1.1456	1.1371	1.1208	1.1051
320	1.2636	1.2491	1.2368	1.2234	1.2121	1.2016	1.1914	1.1823	1.1737	1.1659	1.1575	1.1490	1.1321	1.1258
330	1.2846	1.2686	1.2541	1.2407	1.2285	1.2172	1.2060	1.1961	1.1871	1.1787	1.1703	1.1613	1.1438	1.1261
340	1.3061	1.2885	1.2727	1.2581	1.2449	1.2326	1.2218	1.2117	1.2016	1.1921	1.1838	1.1738	1.1556	1.1371
350	1.3296	1.3101	1.2927	1.2768	1.2625	1.2493	1.2374	1.2271	1.2168	1.2069	1.1968	1.1864	1.1676	1.1485
360	1.3558	1.3342	1.3151	1.2978	1.2821	1.2677	1.2545	1.2412	1.2308	1.2202	1.2108	1.1998	1.1800	1.1598
370	1.3849	1.3598	1.3382	1.3192	1.3020	1.2860	1.2720	1.2588	1.2466	1.2353	1.2254	1.2156	1.1926	1.1711
380	1.4135	1.3860	1.3616	1.3408	1.3222	1.3051	1.2903	1.2768	1.2631	1.2511	1.2403	1.2282	1.2060	1.1838
390	1.4445	1.4141	1.3886	1.3650	1.3445	1.3259	1.3092	1.2938	1.2800	1.2674	1.2561	1.2436	1.2193	1.1962
400	1.4790	1.4443	1.4151	1.3896	1.3672	1.3469	1.3284	1.3122	1.2976	1.2843	1.2727	1.2591	1.2384	1.2092
410	1.5153	1.4759	1.4428	1.4145	1.3897	1.3677	1.3495	1.3320	1.3161	1.3021	1.2897	1.2753	1.2479	1.2228
420	1.5546	1.5096	1.4726	1.4413	1.4121	1.3861	1.3701	1.3521	1.3355	1.3202	1.3069	1.2922	1.2632	1.2361
430	1.5941	1.5448	1.5082	1.4695	1.4365	1.4113	1.3920	1.3731	1.3560	1.3390	1.3252	1.3097	1.2786	1.2505
440	1.6411	1.5823	1.5355	1.4970	1.4638	1.4351	1.4137	1.3944	1.3753	1.3580	1.3437	1.3275	1.2944	1.2650
450	1.6909	1.6237	1.5711	1.5278	1.4912	1.4597	1.4370	1.4165	1.3968	1.3780	1.3624	1.3459	1.3103	1.2800
460	1.7452	1.6684	1.6095	1.5612	1.5208	1.4861	1.4605	1.4392	1.4179	1.3981	1.3815	1.3644	1.3270	1.2947

TABLE 1 (Continued)
Specific Volumes of Water
Pressure in Bars

Temp. °C.	100	150	200	250	300	350	400	450	500	600	700	800
470	30.61	19.38	13.87	10.01	7.61	5.845	4.572	3.687	3.033	2.392	2.092	1.924
480	31.21	19.36	13.97	10.41	7.99	6.24	4.938	4.002	3.307	2.653	2.296	2.004
490	31.80	20.34	14.38	10.79	8.35	6.61	5.322	4.335	3.598	2.939	2.589	2.094
500	32.35	20.77	14.77	11.16	8.71	6.96	5.623	4.641	3.890	2.939	2.462	2.188
510	32.94	21.22	15.15	11.52	9.05	7.29	5.925	4.918	4.166	3.143	2.599	2.298
520	33.48	21.64	15.50	11.85	9.37	7.60	6.218	5.181	4.422	3.347	2.746	2.400
530	34.01	22.04	15.84	12.16	9.68	7.896	6.498	5.44	4.663	3.550	2.899	2.514
540	34.53	22.42	16.16	12.97	9.97	8.179	6.773	5.684	4.891	3.751	3.059	2.631
550	35.09	22.81	16.49	12.78	10.24	8.449	7.040	5.920	5.108	3.950	3.222	2.753
560	35.62	23.15	16.79	13.05	10.49	8.71	7.289	6.143	5.39	4.145	3.377	2.880
570	36.14	23.57	17.12	13.34	10.75	8.94	7.522	6.369	5.535	4.386	3.530	3.012
580	36.66	23.94	17.45	13.62	11.00	9.18	7.75	6.588	5.731	4.518	3.681	3.144
590	37.22	24.33	17.77	13.90	11.25	9.40	7.965	6.800	5.927	4.686	3.829	3.271
600	37.78	24.74	18.11	14.21	11.51	9.650	8.172	7.012	6.114	4.847	3.974	3.396
610	38.284	25.118	18.422	14.471	11.750	9.854	8.3794	7.218	6.301	5.0231	4.1404	3.5254
620	38.789	25.490	18.737	14.729	11.976	10.057	8.5704	7.417	6.483	5.1700	4.2709	3.6408
630	39.308	25.886	19.047	14.982	12.204	10.263	8.7641	7.609	6.659	5.3214	4.4058	3.7591
640	39.777	26.246	19.338	15.236	12.420	10.461	8.9477	7.788	6.828	5.4695	4.5378	3.8756
650	40.290	26.524	19.637	15.477	12.634	10.653	9.1265	7.9668	6.996	5.6157	4.6702	3.9836
660	40.783	26.997	19.912	15.715	12.848	10.845	9.3040	8.1294	7.1638	5.7578	4.7996	4.1079
670	41.271	27.374	20.202	15.954	13.068	11.033	9.4786	8.2884	7.3206	5.9007	4.9321	4.2265
680	41.701	27.708	20.462	16.173	13.248	11.210	9.6422	8.4361	7.4693	6.0371	5.0563	4.3399
690	42.122	28.042	20.721	16.396	13.440	11.388	9.8029	8.5866	7.6120	6.1718	5.1802	4.4511
700	42.517	28.344	20.978	16.600	13.638	11.568	9.9700	8.7389	7.7651	6.3079	5.3041	4.5626
710	42.918	28.686	21.222	16.840	13.842	11.750	10.138	8.8868	7.9113	6.4403	5.4253	4.6709
720	43.233	28.960	21.463	17.050	14.029	11.917	10.287	8.9801	8.0508	6.5664	5.5395	4.7787
730	43.680	29.239	21.696	17.247	14.206	12.077	10.436	9.1650	8.1896	6.6925	5.6538	4.8768

TABLE 1 (Continued)
Specific Volumes of Water
Pressure in Bars

Temp °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
470	1.8029	1.7168	1.6496	1.5959	1.5514	1.5135	1.4851	1.4624	1.4398	1.4192	1.4015	1.3893	1.3439	1.3101
480	1.8649	1.7661	1.6919	1.6325	1.5836	1.5420	1.5101	1.4852	1.4620	1.4404	1.4214	1.4026	1.3606	1.3257
490	1.9344	1.8223	1.7391	1.6731	1.6191	1.5735	1.5370	1.5091	1.4845	1.4631	1.4430	1.4212	1.3779	1.3411
500	2.0060	1.8794	1.7866	1.7137	1.6546	1.6048	1.5653	1.5363	1.5078	1.4860	1.4607	1.4402	1.3953	1.3566
510	2.0853	1.9422	1.8389	1.7684	1.6935	1.6392	1.5946	1.5630	1.5310	1.5046	1.4816	1.4603	1.4131	1.3726
520	2.1682	2.0073	1.8922	1.8037	1.7328	1.6737	1.6261	1.5897	1.5555	1.5274	1.5033	1.4803	1.4311	1.3885
530	2.2578	2.0801	1.9624	1.8651	1.7775	1.7132	1.6592	1.6184	1.5814	1.5511	1.5242	1.5008	1.4495	1.4060
540	2.3509	2.1560	2.0150	1.9083	1.8238	1.7539	1.6941	1.6490	1.6081	1.5754	1.5470	1.5225	1.4683	1.4217
550	2.4503	2.2373	2.0622	1.9654	1.8784	1.7977	1.7315	1.6812	1.6369	1.6011	1.5700	1.5440	1.4872	1.4383
560	2.5553	2.3234	2.1352	2.0258	1.9257	1.8437	1.7708	1.7161	1.6670	1.6283	1.5940	1.5661	1.5257	1.4842
570	2.6625	2.4140	2.2289	2.0904	1.9817	1.8980	1.8123	1.7528	1.6990	1.6570	1.6194	1.5888	1.5280	1.4715
580	2.774	2.5051	2.3055	2.1557	2.0381	1.9425	1.8550	1.7906	1.7314	1.6868	1.6460	1.6124	1.5446	1.4891
590	2.8796	2.5928	2.3796	2.2190	2.0925	1.9901	1.9012	1.8300	1.7659	1.7172	1.6736	1.6370	1.5648	1.5069
600	2.9838	2.6802	2.4479	2.2776	2.1432	2.0347	1.9496	1.8718	1.8024	1.7501	1.7026	1.6630	1.5856	1.5252
610	3.0926	2.7718	2.5327	2.3501	2.2072	2.0914	1.9992	1.9155	1.8414	1.7842	1.7328	1.6908	1.6065	1.5437
620	3.1910	2.8562	2.6061	2.4142	2.2628	2.1410	2.044	1.9612	1.8826	1.8190	1.7644	1.7193	1.6285	1.5627
630	3.2926	2.9485	2.6821	2.4806	2.3213	2.1932	2.091	2.003	1.9240	1.8547	1.7983	1.7482	1.6515	1.5818
640	3.3942	3.0317	2.7593	2.5484	2.3814	2.2471	2.141	2.047	1.9687	1.8928	1.8310	1.7990	1.6745	1.6020
650	3.4977	3.1230	2.8391	2.6188	2.4489	2.3034	2.189	2.089	2.006	1.9320	1.8673	1.8110	1.7008	1.6214
660	3.5993	3.2141	2.9197	2.6904	2.5077	2.3607	2.241	2.136	2.049	1.9730	1.9080	1.8438	1.7262	1.6424
670	3.7045	3.3090	3.0038	2.7655	2.5745	2.4210	2.292	2.181	2.089	2.012	1.9400	1.8792	1.7528	1.6641
680	3.8077	3.4018	3.0866	2.8384	2.6406	2.4805	2.344	2.232	2.132	2.051	1.9775	1.9130	1.7801	1.6868
690	3.9088	3.4921	3.1676	2.9120	2.7067	2.5394	2.396	2.275	2.176	2.090	2.014	1.9480	1.8092	1.7102
700	4.0096	3.5828	3.2491	2.9851	2.7715	2.5990	2.449	2.323	2.219	2.131	2.050	1.9891	1.8391	1.7346
710	4.1074	3.6709	3.3286	3.0565	2.8359	2.6675	2.503	2.371	2.262	2.171	2.087	2.016	1.8611	1.7596
720	4.2006	3.7548	3.4047	3.1251	2.8983	2.7145	2.556	2.421	2.308	2.211	2.126	2.050	1.8898	1.7850
730	4.2933	3.8384	3.4806	3.1940	2.9612	2.7717	2.610	2.471	2.360	2.255	2.169	2.080	1.9338	1.8115

TABLE 1 (Continued)
Specific Volumes of Water
Pressure in Bars

Temp. °C.	100	150	200	250	300	350	400	450	500	600	700	800
740	43.994	29.533	21.949	17.464	14.390	12.286	10.379	9.307	8.3180	6.8110	5.7620	4.9756
750	44.364	29.815	22.208	17.665	14.568	12.397	10.738	9.4631	8.4573	6.9381	5.8761	5.0792
760	44.682	30.084	22.441	17.863	14.747	12.556	10.858	9.5686	8.5704	7.0467	5.9769	5.1743
770	45.065	30.395	22.691	18.066	14.929	12.721	11.024	9.7286	8.7105	7.1780	6.0942	5.2815
780	45.454	30.693	22.967	18.301	15.137	12.906	11.198	9.891	8.8550	7.3080	6.2069	5.3856
790	45.808	30.959	23.148	18.484	15.295	13.044	11.317	9.9940	8.9670	7.4117	6.3091	5.4809
800	46.082	31.201	23.391	18.656	15.432	13.157	11.454	10.141	9.0925	7.5289	6.4156	5.5797
810	46.49	31.48	23.61	18.87	15.65	13.31	11.62	10.27	9.215	7.649	6.518	5.669
820	46.82	31.74	23.84	19.06	15.82	13.44	11.76	10.40	9.340	7.762	6.617	5.757
830	47.19	32.00	24.07	19.24	16.00	13.59	11.90	10.53	9.462	7.872	6.713	5.845
840	47.58	32.26	24.30	19.43	16.17	13.74	12.06	10.67	9.581	7.979	6.807	5.933
850	47.96	32.52	24.53	19.62	16.35	13.97	12.20	10.80	9.704	8.085	6.902	6.020
860	48.21	32.77	24.74	19.81	16.52	14.01	12.34	10.93	9.830	8.191	6.998	6.106
870	48.54	33.03	24.97	20.00	16.69	14.14	12.49	11.07	9.952	8.296	7.094	6.195
880	48.87	33.28	25.19	20.18	16.86	14.27	12.63	11.19	10.07	8.400	7.187	6.270
890	49.21	33.53	25.42	20.37	17.03	14.40	12.76	11.33	10.17	8.500	7.280	6.355
900	49.54	33.78	25.74	20.57	17.20	14.53	12.90	11.45	10.28	8.602	7.373	6.450
910	49.87	34.03	25.86	20.75	17.37	14.61	13.04	11.58	10.40	8.704	7.468	6.536
920	50.21	34.28	26.07	20.93	17.54	14.79	13.16	11.70	10.52	8.805	7.561	6.620
930	50.54	34.53	26.29	21.11	17.71	14.91	13.30	11.81	10.62	8.905	7.653	6.701
940	50.87	34.78	26.52	21.30	17.87	15.02	13.42	11.95	10.72	9.030	7.745	6.783
950	51.22	35.03	26.73	21.49	18.04	15.14	13.56	12.07	10.82	9.100	7.894	6.862
960	51.54	35.28	26.94	21.66	18.21	15.26	13.68	12.19	10.92	9.196	7.924	6.940
970	51.89	35.53	27.18	21.84	18.38	15.37	13.72	12.31	11.02	9.290	8.013	7.018
980	52.23	35.78	27.39	22.03	18.56	15.49	13.94	12.43	11.11	9.382	8.100	7.090
990	52.55	36.04	27.62	22.22	18.73	15.60	14.07	12.55	11.20	9.473	8.185	7.165
1000	52.90	36.29	27.84	22.40	18.90	15.71	14.20	12.67	11.30	9.563	8.269	7.237

TABLE 1 (Continued)
Specific Volumes of Water
Pressure in Bars

Temp °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
740	4.8844	3.9215	3.5563	3.2628	3.0240	2.8292	2.666	2.523	2.400	2.298	2.207	2.126	1.9678	1.8390
750	4.4774	4.0062	3.6386	3.3386	3.0888	2.8884	2.720	2.572	2.445	2.339	2.244	2.161	1.994	1.8661
760	4.5660	4.0881	3.7090	3.4024	3.1521	2.9465	2.774	2.621	2.490	2.382	2.284	2.198	2.024	1.8747
770	4.6583	4.1772	3.7904	3.4765	3.2205	3.0090	2.830	2.671	2.537	2.426	2.324	2.235	2.054	1.9245
780	4.7689	4.2669	3.8720	3.5515	3.2896	3.0723	2.882	2.722	2.581	2.468	2.364	2.273	2.087	1.945
790	4.8475	4.3476	3.9464	3.6206	3.3539	3.1312	2.939	2.773	2.632	2.513	2.404	2.311	2.120	1.972
800	4.9397	4.4338	4.0259	3.6928	3.4207	3.1927	2.994	2.824	2.679	2.556	2.445	2.350	2.152	2.000
810	5.030	4.506	4.099	3.760	3.481	3.250	3.049	2.874	2.725	2.600	2.488	2.387	2.187	2.027
820	5.120	4.587	4.172	3.829	3.546	3.309	3.104	2.926	2.778	2.644	2.529	2.428	2.222	2.066
830	5.212	4.668	4.246	3.896	3.610	3.369	3.160	2.978	2.821	2.688	2.570	2.466	2.258	2.083
840	5.300	4.746	4.318	3.961	3.672	3.428	3.214	3.030	2.869	2.732	2.611	2.505	2.294	2.114
850	5.385	4.825	4.388	4.028	3.732	3.484	3.266	3.080	2.916	2.778	2.652	2.545	2.329	2.144
860	5.462	4.902	4.761	4.095	3.792	3.542	3.322	3.130	2.963	2.823	2.694	2.583	2.366	2.174
870	5.540	4.979	4.832	4.161	3.852	3.599	3.373	3.180	3.011	2.867	2.735	2.623	2.401	2.205
880	5.623	5.055	4.900	4.224	3.913	3.656	3.428	3.230	3.058	2.911	2.776	2.660	2.436	2.235
890	5.702	5.131	4.968	4.287	3.973	3.713	3.479	3.280	3.105	2.954	2.818	2.699	2.472	2.264
900	5.781	5.208	4.784	4.350	4.033	3.770	3.531	3.330	3.152	2.999	2.859	2.738	2.508	2.293
910	5.860	5.282	4.799	4.414	4.091	3.824	3.583	3.379	3.201	3.041	2.900	2.776	2.542	2.328
920	5.933	5.357	4.862	4.477	4.149	3.879	3.633	3.430	3.249	3.085	2.940	2.816	2.579	2.355
930	6.006	5.429	4.926	4.540	4.207	3.932	3.683	3.480	3.295	3.129	2.982	2.858	2.614	2.385
940	6.078	5.497	4.986	4.608	4.266	3.981	3.744	3.529	3.341	3.173	3.023	2.892	2.649	2.416
950	6.146	5.568	5.047	4.662	4.324	4.032	3.785	3.578	3.387	3.218	3.065	2.931	2.682	2.446
960	6.214	5.639	5.107	4.722	4.381	4.082	3.835	3.626	3.433	3.261	3.108	2.969	2.719	2.474
970	6.280	5.705	5.167	4.780	4.439	4.131	3.885	3.674	3.481	3.305	3.149	3.007	2.751	2.502
980	6.343	5.773	5.226	4.837	4.494	4.179	3.935	3.722	3.524	3.349	3.189	3.047	2.785	2.531
990	6.405	5.837	5.288	4.892	4.550	4.226	3.983	3.770	3.570	3.390	3.231	3.085	2.821	2.560
1000	6.466	5.900	5.347	4.948	4.604	4.271	4.035	3.818	3.613	3.436	3.282	3.123	2.854	2.589

TABLE 2
Density of Water
Pressure in Bars

Temp. °C.	100.	150	200	250	300	350	400	450	500	600	700	800
200	.87085	.87437	.87797	.88113	.88470	.88754	.89110		.89720	.90310	.90880	.91435
210	.86916	.86292	.86679	.87015	.87400	.87695	.88040		.88682	.89302	.89900	.90476
220	.86683	.86096	.86490	.86871	.87289	.87598	.87963		.88748	.89396	.89926	.90532
230	.86401	.85842	.86267	.86677	.87072	.87463	.87846		.88769	.89423	.89923	.90567
240	.86041	.85524	.85987	.86429	.86854	.87268	.87675		.88755	.89426	.89926	.90582
250	.85602	.85135	.85641	.86122	.86581	.87021	.87445		.88700	.89376	.89875	.90546
260	.85171	.84765	.85281	.85796	.86291	.86771	.87232		.88695	.89371	.89870	.90543
270	.84743	.84371	.84916	.85456	.85981	.86491	.86986		.88638	.89314	.89813	.90486
280	.84326	.83981	.84556	.85136	.85701	.86251	.86796		.88626	.89302	.89801	.90474
290	.83921	.83596	.84191	.84796	.85391	.85981	.86576		.88621	.89297	.89796	.90469
300	.83526	.83221	.83846	.84471	.85096	.85721	.86346		.88576	.89251	.89750	.90423
310	.83141	.82856	.83501	.84156	.84811	.85466	.86121		.88451	.89126	.89625	.90298
320	.82766	.82491	.83156	.83831	.84506	.85181	.85856		.88376	.89051	.89550	.90223
330	.82401	.82136	.82821	.83506	.84191	.84876	.85561		.88201	.88876	.89375	.90048
340	.82046	.81791	.82496	.83191	.83896	.84601	.85306		.88046	.88721	.89220	.89893
350	.81701	.81456	.82181	.82896	.83621	.84346	.85071		.87801	.88476	.88975	.89648
360	.81366	.81131	.81876	.82601	.83336	.84071	.84806		.87536	.88211	.88710	.89383
370	.81041	.80816	.81581	.82326	.83081	.83846	.84611		.87261	.87936	.88435	.89108
380	.80726	.80511	.81296	.82061	.82846	.83641	.84436		.87046	.87721	.88220	.88893
390	.80421	.80216	.81021	.81806	.82611	.83426	.84241		.86851	.87526	.88025	.88698
400	.80126	.80031	.80856	.81671	.82506	.83341	.84176		.86656	.87331	.87830	.88503
410	.79841	.79756	.80601	.81436	.82291	.83146	.84011		.86471	.87146	.87645	.88318
420	.79566	.79491	.80356	.81211	.82086	.82961	.83846		.86296	.86971	.87470	.88143
430	.79301	.79236	.80121	.81006	.81891	.82786	.83691		.86121	.86796	.87295	.87968
440	.79046	.79091	.80006	.80901	.81806	.82721	.83646		.85956	.86631	.87130	.87803
450	.78801	.78856	.79791	.80716	.81651	.82596	.83541		.85856	.86531	.87030	.87703
460	.78566	.78631	.79586	.80531	.81486	.82451	.83416		.85731	.86406	.86905	.87578

TABLE 2 (Continued)
Density of Water
Pressure in Bars

Temp. °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
200	.91978	.92498	.93008	.93498	.93989	.94414	.9498	.9552	.9607	.9656	.9704	.9748	.9870	.9973
210	.91086	.91578	.92108	.92605	.93089	.93559	.9413	.9471	.9522	.9571	.9619	.9663	.9785	.9893
220	.90115	.90681	.91236	.91746	.92248	.92734	.93393	.9403	.9468	.9534	.9593	.9658	.9780	.9898
230	.89167	.89755	.90325	.90865	.91385	.91887	.9248	.9309	.9360	.9414	.9468	.9525	.9647	.9765
240	.88189	.88802	.89388	.89945	.90485	.91005	.9167	.9236	.9300	.9368	.9431	.9498	.9620	.9738
250	.87183	.87823	.88439	.89022	.89584	.90122	.9063	.9117	.9173	.9231	.9271	.9322	.9444	.9562
260	.86184	.86805	.87445	.88055	.88640	.89198	.8973	.9025	.9081	.9129	.9183	.9235	.9357	.9475
270	.85095	.85767	.86437	.87075	.87687	.88267	.8880	.8931	.8990	.9040	.9094	.9149	.9271	.9388
280	.83952	.84690	.85390	.86058	.86696	.87299	.8787	.8840	.8897	.8949	.9006	.9062	.9183	.9304
290	.82788	.83586	.84300	.85001	.85669	.86299	.8691	.8747	.8804	.8858	.8913	.8973	.9095	.9219
300	.81609	.82429	.83201	.83938	.84635	.85295	.8591	.8651	.8710	.8766	.8823	.8883	.9009	.9135
310	.80395	.81263	.82077	.82852	.83580	.84270	.8494	.8556	.8617	.8673	.8729	.8794	.8922	.9048
320	.79133	.80056	.80918	.81736	.82499	.83223	.8393	.8458	.8520	.8577	.8639	.8703	.8833	.8962
330	.77840	.78821	.79734	.80594	.81395	.82155	.8291	.8360	.8423	.8483	.8545	.8611	.8742	.8880
340	.76561	.77603	.78573	.79481	.80324	.81123	.8184	.8252	.8322	.8388	.8447	.8519	.8653	.8794
350	.75206	.76327	.77355	.78315	.79203	.80044	.8081	.8149	.8225	.8292	.8355	.8426	.8564	.8707
360	.73783	.74950	.76038	.77052	.77994	.78882	.7971	.8056	.8124	.8195	.8259	.8334	.8474	.8622
370	.72205	.73540	.74727	.75803	.76804	.77760	.7861	.7944	.8021	.8095	.8160	.8239	.8385	.8538
380	.70618	.72199	.73439	.74578	.75681	.76621	.7750	.7837	.7917	.7992	.8062	.8141	.8291	.8447
390	.69024	.70714	.72044	.73287	.74437	.75418	.7638	.7729	.7812	.7890	.7961	.8041	.8201	.8369
400	.67613	.69283	.70663	.71956	.73142	.74242	.7525	.7620	.7706	.7786	.7857	.7942	.8241	.8369
410	.65993	.67765	.69307	.70692	.71984	.73114	.7410	.7507	.7598	.7679	.7753	.7841	.8213	.8177
420	.64322	.66239	.67905	.69381	.70716	.72067	.73298	.7446	.7557	.7664	.7761	.7868	.8261	.8089
430	.62729	.64816	.66609	.68186	.69612	.70906	.72183	.7342	.7468	.7586	.7706	.7821	.8229	.7996
440	.60952	.63197	.65123	.66799	.68313	.69681	.70978	.72171	.73371	.7456	.7576	.7696	.8119	.7905
450	.59140	.61587	.63647	.65453	.67067	.68504	.69868	.71161	.72456	.73756	.75056	.76356	.8069	.7812
460	.57298	.59936	.62131	.64051	.65751	.67286	.68646	.70052	.71452	.72852	.74252	.75652	.8009	.7723

TABLE 2 (Continued)
Density of Water
Pressure in Bars

Temp. °C.	100	150	200	250	300	350	400	450	500	600	700	800
470	.03267	.06160	.07369	.09990	.13140	.17108	.21872	.27344	.32970	.41981	.47801	.51976
480	.03304	.05084	.07158	.09606	.12676	.16025	.20251	.24987	.30288	.39169	.45390	.49900
490	.03145	.04917	.06955	.09268	.11976	.15128	.18789	.23008	.27793	.36509	.42986	.47755
500	.03091	.04814	.06772	.08960	.11479	.14363	.17784	.21647	.25706	.34026	.40617	.45703
510	.03036	.04712	.06601	.08680	.11046	.13717	.16877	.20333	.24003	.31816	.38476	.43610
520	.02987	.04621	.06453	.08438	.10673	.13149	.16066	.19301	.22814	.29877	.36416	.41666
530	.02940	.04537	.06314	.08224	.10330	.12664	.15389	.18392	.21445	.28169	.34484	.39777
540	.02896	.04460	.06188	.07710	.10030	.12199	.14764	.17593	.20445	.26659	.32711	.38008
550	.02850	.04383	.06064	.07326	.09765	.11885	.14204	.16891	.19877	.25316	.31036	.36324
560	.02807	.04320	.05957	.07161	.09534	.11456	.13719	.16278	.18761	.24125	.29612	.34722
570	.02767	.04243	.05840	.07005	.09303	.11177	.13294	.15701	.18066	.23063	.28328	.33200
580	.02728	.04177	.05736	.07039	.09069	.10896	.12909	.15179	.17448	.22133	.27166	.31806
590	.02687	.04110	.05628	.07183	.08996	.10836	.12554	.14705	.16871	.21340	.26116	.30571
600	.02647	.04042	.05520	.07038	.08685	.10371	.12236	.14261	.16355	.20681	.25163	.29446
610	.02612	.03982	.05428	.06910	.08510	.10148	.11984	.13864	.15870	.19908	.24152	.28365
620	.02578	.03923	.05337	.06759	.08350	.09943	.11668	.13482	.15424	.19442	.23414	.27446
630	.02544	.03863	.05250	.06670	.08194	.09744	.11411	.13142	.15017	.18792	.22697	.26602
640	.02514	.03810	.05171	.06563	.08051	.09559	.11176	.12840	.14645	.18283	.22037	.25802
650	.02482	.03755	.05095	.06461	.07915	.09387	.10957	.12562	.14292	.17807	.21412	.25040
660	.02452	.03704	.05027	.06363	.07783	.09220	.10748	.12301	.13951	.17369	.20835	.24343
670	.02423	.03658	.04950	.06268	.07659	.09063	.10565	.12065	.13660	.16947	.20276	.23660
680	.02398	.03609	.04867	.06133	.07548	.08920	.10371	.11861	.13388	.16564	.19777	.23042
690	.02374	.03568	.04826	.06099	.07440	.08791	.10201	.11646	.13131	.16204	.19304	.22466
700	.02352	.03528	.04768	.06024	.07332	.08644	.10080	.11443	.12878	.16863	.19863	.21917
710	.02330	.03486	.04712	.05938	.07224	.08510	.09868	.11260	.12640	.16527	.18432	.21409
720	.02313	.03453	.04659	.05865	.07126	.08391	.09731	.11074	.12421	.16229	.18052	.20948
730	.02292	.03420	.04609	.05798	.07039	.08280	.09582	.10911	.12212	.14942	.17687	.20507

TABLE 2 (Continued)
Density of Water
Pressure in Bars

Temp. °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
470	55465	55280	60623	62658	64455	66075	6733	6838	6945	7046	7135	7226	7441	7633
480	53621	53621	59104	61255	63147	64860	6622	6783	6839	6942	7035	7129	7349	7543
490	51693	51693	57501	59768	61760	63549	6506	6626	6736	6820	6892	6943	7166	7371
500	49850	49850	55970	58350	60436	62310	6388	6509	6632	6747	6846	6943	7166	7371
510	47954	47954	54379	56869	59047	61004	6270	6397	6531	6646	6749	6847	7076	7285
520	46121	46121	52816	55441	57708	59745	6149	6290	6428	6547	6652	6755	6987	7202
530	44280	44280	51218	53904	56256	58369	6027	6192	6323	6447	6560	6668	6898	7117
540	42536	42536	49381	52400	54829	57013	5902	6064	6218	6347	6464	6567	6810	7033
550	40810	40810	48026	50878	53378	55626	5775	5948	6109	6245	6369	6476	6724	6952
560	39134	39134	46442	49362	51927	54237	5647	5827	5998	6141	6273	6385	6654	6876
570	37530	37530	44864	47887	50461	52825	5519	5705	5885	6035	6175	6294	6587	6795
580	36046	36046	43373	46387	49064	51478	5380	5564	5755	5928	6075	6201	6474	6715
590	34726	34726	42023	45065	47789	50247	5259	5464	5662	5833	5975	6108	6390	6636
600	33514	33514	40850	43905	46659	49146	5129	5342	5548	5713	5873	6013	6306	6556
610	32335	32335	39483	42539	45306	47813	5002	5220	5430	5604	5771	5914	6224	6477
620	31188	31188	38371	41421	44193	46707	4899	5098	5311	5497	5667	5816	6140	6399
630	30071	30071	37284	40312	43079	45595	4782	4992	5197	5391	5566	5720	6018	6321
640	28962	28962	36241	39240	41992	44500	4670	4885	5079	5263	5461	5588	5911	6242
650	27850	27850	35222	38185	40917	43413	4568	4796	4985	5175	5355	5521	5879	6167
660	26783	26783	34250	37168	39877	42359	4462	4681	4882	5068	5249	5422	5792	6087
670	25694	25694	33291	36159	38841	41305	4363	4585	4798	4970	5154	5327	5705	6009
680	24626	24626	32368	35218	37870	40313	4266	4486	4690	4875	5056	5227	5617	5928
690	23566	23566	31469	34340	36958	39378	4173	4395	4605	4784	4965	5138	5527	5847
700	22490	22490	30777	33499	36081	38475	4083	4304	4508	4692	4878	5050	5437	5765
710	21436	21436	30042	32717	35261	37628	3995	4217	4420	4606	4791	4960	5360	5688
720	20396	20396	29371	31998	34502	36839	3912	4130	4332	4522	4702	4878	5288	5601
730	19392	19392	28730	31308	33770	36078	3831	4046	4255	4434	4616	4807	5220	5520

TABLE 2 (Continued)
Density of Water
Pressure in Bars

Temp. °C.	100	150	200	250	300	350	400	450	500	600	700	800
740	.02273	.03886	.04556	.05726	.06949	.08172	.09452	.10746	.12022	.14682	.17355	.20098
750	.02284	.03864	.04504	.05662	.06864	.08066	.09311	.10578	.11824	.14413	.17018	.19688
760	.02298	.03824	.04456	.05598	.06781	.07964	.09209	.10454	.11668	.14191	.16731	.19326
770	.02318	.03290	.04407	.05535	.06698	.07861	.09071	.10281	.11431	.13941	.16409	.18934
780	.02200	.03258	.04384	.05464	.06606	.07748	.08880	.10112	.11293	.13693	.16111	.18568
790	.02183	.03230	.04320	.05410	.06538	.07666	.08886	.10006	.11152	.13492	.15850	.18245
800	.02170	.03205	.04275	.05360	.06480	.07600	.08730	.09860	.10998	.13282	.15597	.17923
810	.02244	.03176	.04235	.05299	.06390	.07513	.08606	.09737	.10851	.13073	.15342	.17639
820	.02135	.03150	.04194	.05249	.06321	.07440	.08508	.09615	.10706	.12883	.15112	.17370
830	.02119	.03125	.04154	.05237	.06350	.07488	.08403	.09496	.10568	.12708	.14896	.17108
840	.02111	.03099	.04115	.05146	.06184	.07278	.08292	.09372	.10437	.12532	.14690	.16854
850	.02089	.03075	.04076	.05097	.06116	.07210	.08197	.09259	.10305	.12368	.14488	.16611
860	.02074	.03051	.04042	.05048	.06053	.07138	.08104	.09149	.10172	.12208	.14289	.16377
870	.02060	.03027	.04005	.05000	.06004	.07072	.08006	.09033	.10048	.12054	.14096	.16142
880	.02046	.03004	.03988	.04955	.05931	.07008	.07918	.08937	.09930	.11904	.13914	.15946
890	.02032	.02982	.03938	.04909	.05872	.06944	.07837	.08826	.09803	.11764	.13756	.15710
900	.02018	.02960	.03885	.04861	.05814	.06882	.07762	.08734	.09723	.11625	.13563	.15503
910	.02005	.02938	.03866	.04819	.05757	.06821	.07669	.08636	.09615	.11488	.13390	.15299
920	.01991	.02917	.03835	.04778	.05701	.06761	.07599	.08547	.09506	.11357	.13225	.15105
930	.01979	.02896	.03803	.04737	.05647	.06707	.07619	.08563	.09412	.11229	.13066	.14923
940	.01965	.02875	.03770	.04695	.05596	.06658	.07451	.08368	.09238	.11074	.12911	.14742
950	.01952	.02854	.03741	.04655	.05543	.06605	.07375	.08285	.09242	.10989	.12764	.14573
960	.01940	.02834	.03711	.04617	.05491	.06553	.07310	.08203	.09157	.10874	.12619	.14409
970	.01927	.02814	.03679	.04579	.05441	.06508	.07269	.08123	.09074	.10764	.12479	.14249
980	.01914	.02794	.03650	.04529	.05388	.06454	.07174	.08045	.09001	.10659	.12345	.14104
990	.01902	.02774	.03620	.04500	.05339	.06410	.07107	.07968	.08928	.10556	.12217	.13956
1000	.01890	.02755	.03591	.04464	.05291	.06356	.07042	.07893	.08850	.10456	.12093	.13817

TABLE 2 (Continued)
Density of Water
Pressure in Bars

Temp. °C.	900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2250	2500
740	22808	25500	26119	30648	33068	35345	3750	3983	4166	4351	4531	4703	5081	5437
750	22834	24961	27519	29997	32876	34621	3676	3988	4089	4275	4466	4627	5015	5358
760	21901	24461	26961	29391	31724	33938	3604	3815	4016	4198	4378	4549	4940	5284
770	21444	23939	26382	28764	31051	33233	3433	3743	3941	4123	4302	4474	4868	5196
780	21018	23436	25826	28187	30399	32458	3469	3673	3874	4051	4230	4399	4791	5141
790	20629	23001	25339	27619	29839	31936	3402	3606	3799	3979	4159	4327	4716	5070
800	20244	22554	24889	27079	29283	31321	3340	3541	3732	3912	4089	4255	4646	5000
810	19880	22192	24396	26595	28727	30769	3279	3479	3669	3846	4019	4129	4572	4933
820	19531	21800	23964	26116	28200	30220	3221	3417	3606	3782	3954	4118	4500	4863
830	19186	21422	23551	25667	27700	29653	3164	3357	3544	3720	3891	4055	4428	4800
840	18867	21070	23158	25246	27283	29180	3111	3300	3485	3660	3829	3992	4359	4730
850	18570	20725	22789	24821	26795	28702	3069	3246	3429	3609	3770	3929	4293	4664
860	18308	20399	22403	24420	26371	28252	3010	3194	3374	3543	3711	3871	4226	4599
870	18050	20084	22065	24032	25960	27785	2964	3144	3321	3478	3656	3812	4166	4535
880	17784	19782	21739	23674	25555	27392	2917	3095	3270	3435	3602	3759	4105	4474
890	17537	19489	21422	23326	25169	26922	2874	3048	3220	3385	3548	3705	4045	4416
900	17298	19201	21123	22988	24795	26525	2832	3003	3172	3334	3479	3632	3967	4355
910	17064	18932	20837	22655	24443	26150	2790	2959	3124	3288	3448	3602	3933	4295
920	16854	18667	20567	22356	24102	25779	2752	2915	3077	3241	3401	3551	3877	4246
930	16650	18419	20300	22026	23769	25452	2715	2878	3034	3195	3353	3505	3825	4192
940	16428	18191	20056	21724	23441	25119	2670	2833	2983	3151	3307	3467	3775	4139
950	16270	17969	19813	21450	23126	24802	2642	2794	2952	3107	3262	3411	3728	4088
960	16092	17793	19580	21177	22825	24497	2607	2757	2912	3066	3217	3368	3677	4042
970	15923	17538	19353	20920	22527	24197	2574	2721	2875	3025	3175	3325	3635	3996
980	15765	17322	19136	20673	22251	23929	2541	2686	2837	2985	3135	3281	3590	3951
990	15612	17132	18910	20441	21978	23663	2510	2652	2801	2949	3095	3241	3544	3906
1000	15465	16949	18702	20210	21720	23413	2478	2619	2767	2910	3046	3202	3504	3862

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A NEW ARTHRODIRE FROM THE NEW YORK STATE DEVONIAN

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ABSTRACT. The trunk carapace of a new species of arthrodire, *Phlyctenaspis sherwoodi*, is described. Its occurrence in the Late Devonian continental sediments near Gilboa, New York, is surprising, since it belongs to the primitive and typically Early Devonian family, Phlyctenaspidae. The suggestion is made that slowly evolving arthrodire stocks persisted throughout most of the Devonian in a fresh water environment, while the main radiation of the order was taking place in the seas.

AFTER the death of James Hall, director of the New York State Geological Survey, the Walker Museum of the University of Chicago acquired a considerable part of his collection of fossils. In 1947, the few fishes in this collection, together with the other vertebrate fossils in the Walker Museum, were transferred to the Chicago Natural History Museum. The arthrodire plates described in this paper were among this lot. They were collected in 1880 by Andrew Sherwood, "about three miles west of Gilboa, on the road to Stamford, N. Y." The Gilboa of Sherwood's day is now submerged beneath the Schoharie Reservoir; but the locality must have been very near the western boundary of the 1903 or 1945 editions of the Gilboa quadrangle of the U. S. Geological Survey, and probably at an elevation of 1750' to 1850'.

The arthrodire plates occur in a greenish-gray or bluish-gray sandy shale. The rocks are at least partly continental in origin, as shown by the presence of land plants, the fresh water clam, *Amnigenia*, and *Holptychius* scales. Their age, according to G. Arthur Cooper (*in litteris*, Jan. 31, 1949) is probably Genesee or Sherburne, thus within the Genesee group at the base of the Late Devonian. George H. Chadwick (*in litteris*, Jan. 28, 1949) comes to substantially the same conclusions regarding the age of the beds at this locality, placing them either in the top of the Gilboa formation, or more probably at the base of the overlying Onteora red beds. Thus they can be no older than the latest Middle Devonian (Tully), and are probably at the base of the Late Devonian (Genesee). The author visited this region briefly in the company of Dr. Chadwick in April, 1949. Although no fish remains were found, it was established that rocks of very similar lithology occur in this immediate vicinity, and that the earlier estimates of the geologic age were substantially correct.

The probable Late Devonian age of this fossil is of considerable interest, since it belongs quite certainly to *Phlyctænaspis*, a primitive arthrodire of the typically Early Devonian family Phlyctænaspidæ.¹ The only certain records of post-Early Devonian phlyctænaspid are *Buchanosteus* from the Middle Devonian of Australia, and *Actinolepis* (including *Lataspis*) from the Middle Devonian of the Baltic states and northwestern Russia. In Spitzbergen, *Huginaspis* occurs in the upper part of the Gray Hoek series, of which the age may be as late as Middle Devonian. The Late Devonian *Grænländaspis* may be a specialized phlyctænaspid, but is at present of uncertain affinities. The genus *Phlyctænaspis* itself is known from four species in the Coblenzian of Germany, as well as one (*P. acadica*) from New Brunswick. The latter has generally been considered to be of Early Devonian age, but is placed by the Canadian Geological Survey in the base of the Gaspé sandstone and thus may belong in the Middle Devonian.

The material upon which this new species is founded consists of a number of disarticulated plates of the trunk carapace. No remains of the cranial shield are known.

PHLYCTÆNASPIS SHERWOODI,² NEW SPECIES

Type.—The antero-lateral plate on UF 150 in the University of Chicago collection at Chicago Natural History Museum (plate 1, fig. 1). Since there is no certainty that the associated plates on this piece of rock belonged to the same individual, the designation applies only to the antero-lateral.

Occurrence.—Probably from the Late Devonian, base of the Onteora formation, about three miles west of Gilboa, New York.

Diagnosis.—A phlyctænaspid attaining moderate size, characterized particularly by: (1) its very long and relatively

¹ As here used, the Phlyctænaspidæ include the Arctolepidæ of Heintz, 1937, p. 14, and are equivalent to the Dolichothoraci of Stensib, 1944, p. 2.

² Fowler (1947, p. 5) proposes to return to the use of *Phlyctænius* Traquair 1890, since according to the rules of zoological nomenclature this name is not preoccupied by *Phlyctanium* Zittel 1878, a Jurassic sponge. But because it is recommended that the use of a name differing only in termination from another be avoided, and because *Phlyctænaspis* has enjoyed long usage, the latter is here retained. The species is named in honor of the discoverer of these specimens, Andrew Sherwood, a collector for the New York and Pennsylvania Geological Surveys.

narrow MD;³ (2) the unreduced plates of the lateral trunk shield (ADL, PDL, AL, and presumably PL); (3) the long postero-dorsal and antero-ventral processes of AL; (4) the elongate, slender, gently curved SP, with heavy recurved barbs on the inner margin and small barbs on the outer edge; and (5) the relatively fine tubercles on the outer surface, arranged more or less concentrically in a linear fashion near the margins of the plates (plate 1, fig. 2).

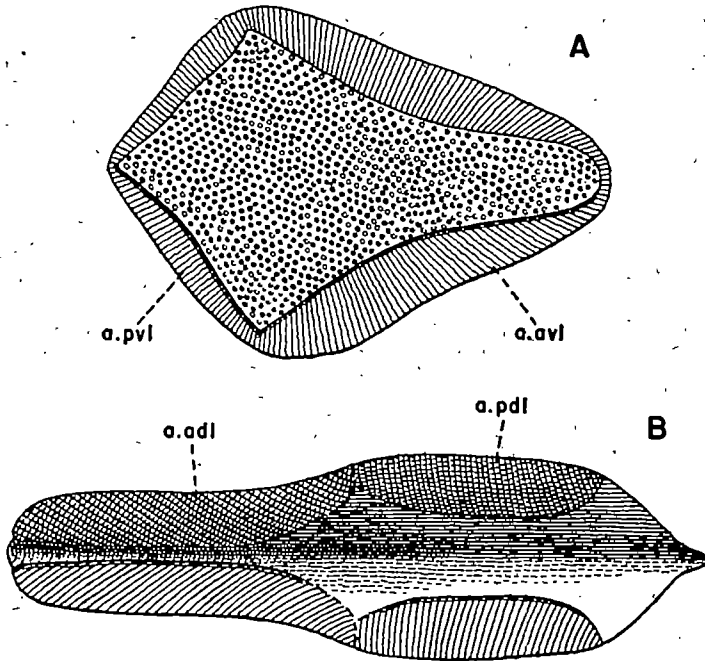


Fig. 1. A. Postero-median-ventral plate, outer surface. B. Median-dorsal plate, inner surface. About size of large individual. a.adl, area that overlaps ADL; a.avl, area overlapped by AVL; a.pdl, area that overlaps PDL; a.pvl, area overlapped by PVL.

³ The plates of the trunk carapace will hereafter be designated by abbreviations of their names, as follows:

- ADL—antero-dorso-lateral
- AL—antero-lateral
- AMV—antero-median-ventral
- AVL—antero-ventro-lateral
- IL—intero-lateral
- MD—median-dorsal
- PDL—postero-dorso-lateral
- PL—postero-lateral
- PMV—postero-median-ventral
- PVL—postero-ventro-lateral
- SP—spinal

Median dorsal plate (MD) (text-fig. 1B).—Two examples occur in the collection, both of which are preserved largely as impressions of the inner side; one is nearly complete, while the other is an impression of the posterior half of the plate. Among the Phlyctenaspidae, the MD resembles most closely that of *Phlyctenaspis acadica* (Whiteaves) as restored by Heintz (1933, text-fig. 3), but is proportionately much longer and narrower, exceeding all other members of the family in this respect. The anterior half of the plate is narrow with sub-parallel sides and a rounded anterior termination, differing from the indented anterior end in *P. acadica*. Near the middle of its length the plate widens somewhat, continuing posteriorly with sub-parallel sides until it tapers to a posterior point. The MD is only moderately arched and lacks a distinct median ridge externally or internally. The large areas by which the MD overlaps the PDL's are shown on UF 159, while the overlap areas for the ADL's are seen on UF 157 to reach nearly to the midline.

The total length of MD on UF 157 is estimated to be 112 mm., and its maximum width in the posterior part is about 30 mm. The MD on UF 159 is smaller, having a maximum width posteriorly of 26 mm.

Antero-dorso-lateral plate (ADL) (text-fig. 2).—Three examples of this plate are present. On UF 157 is an imperfect impression of the inner side of the plate; on UF 149 are good impressions of both the inner and outer sides in counterpart,

PLATE 1.

Fig. 1. Type of *Phlyctenaspis sherwoodi*. UF 150 in Chicago Natural History Museum, $\times 5/2$; largely an impression of the inner surface of the left AL, but showing some of the tuberculated outer surface in the postero-dorsal corner.

Fig. 2. PMV of *P. sherwoodi*, UF 157, $\times 2$, showing the character of the tuberculation of the outer surface.

PLATE 2.

Restoration of the trunk shield of *P. sherwoodi*; the size is about that of a moderately small individual.

Fig. 1. Dorsal view.

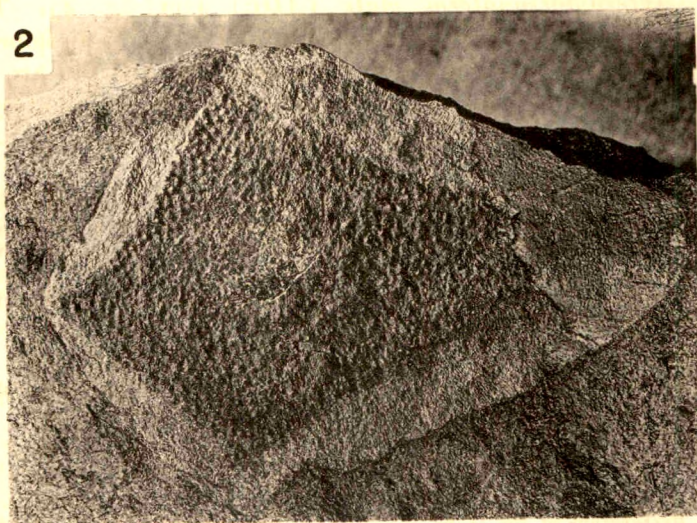
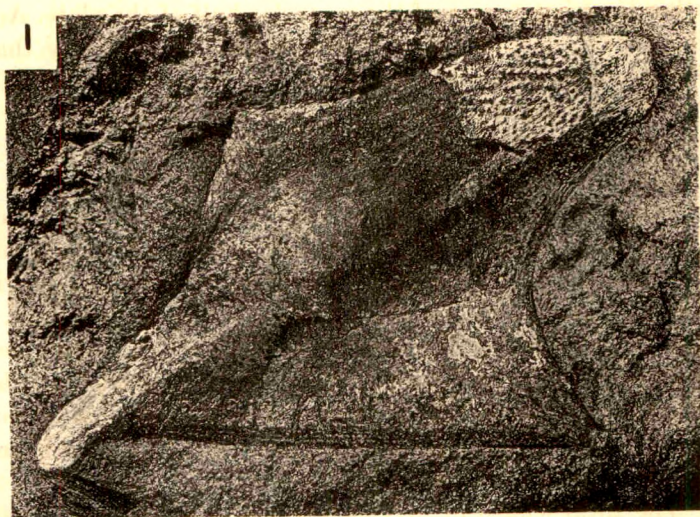
Fig. 2. Obliquely anterior view.

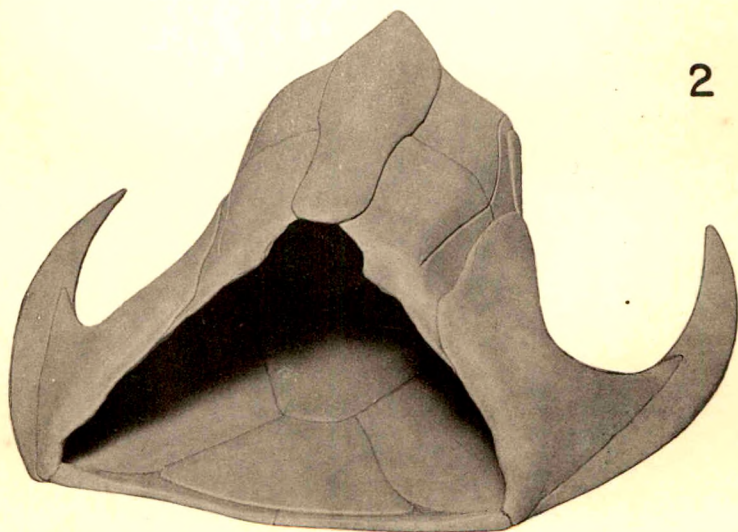
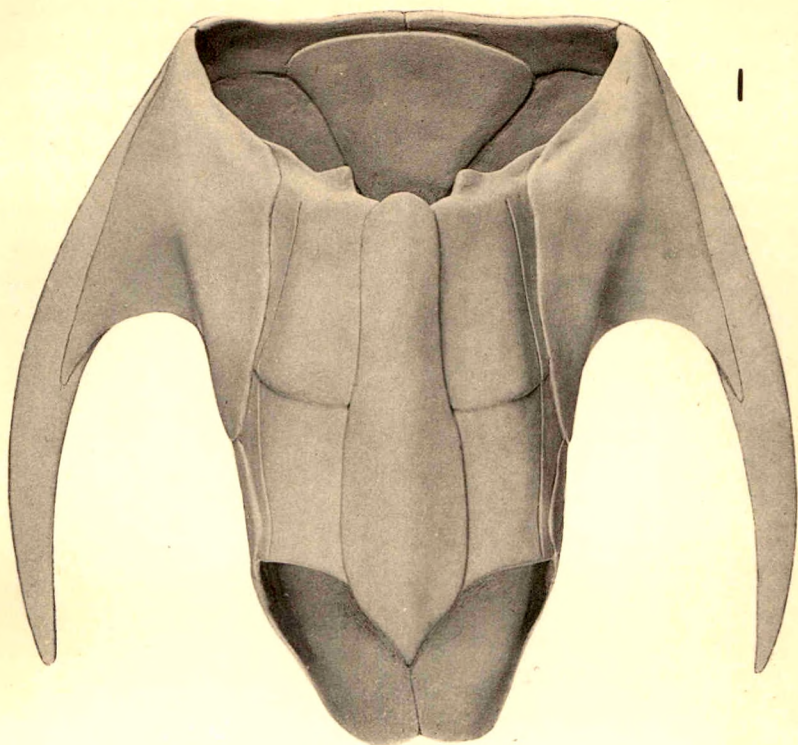
PLATE 3.

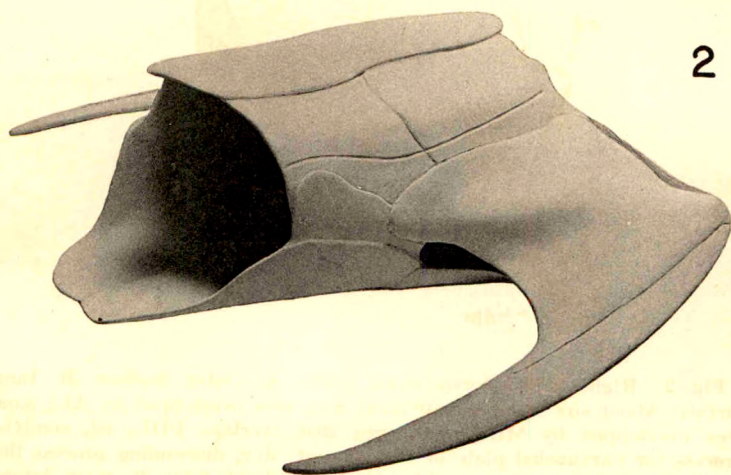
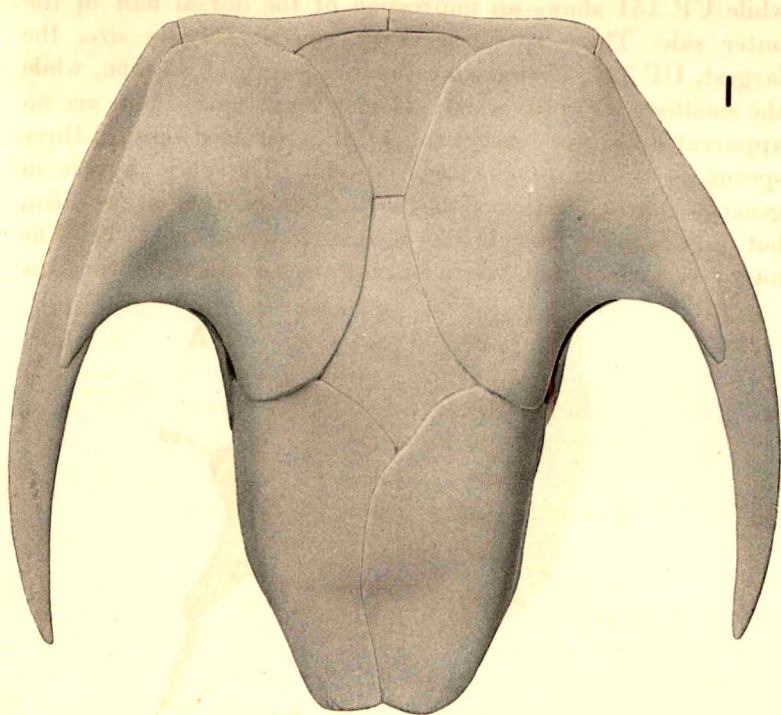
Restoration of the trunk shield of *P. sherwoodi*; the size is about that of a moderately small individual.

Fig. 1. Ventral view.

Fig. 2. Postero-lateral view.







while UF 151 shows an impression of the dorsal half of the outer side. These specimens vary considerably in size, the largest, UF 157, having an estimated length of 55 mm., while the smallest, UF 149, is only 21 mm. long. Since there are no apparent differences except in size, it is assumed that all three specimens belong to the same species. The plate agrees in general characteristics with that of *Phlyctænaspis acadica*, but is relatively longer and less deep dorso-ventrally. The narrower proportions are to be taken as an indication that the

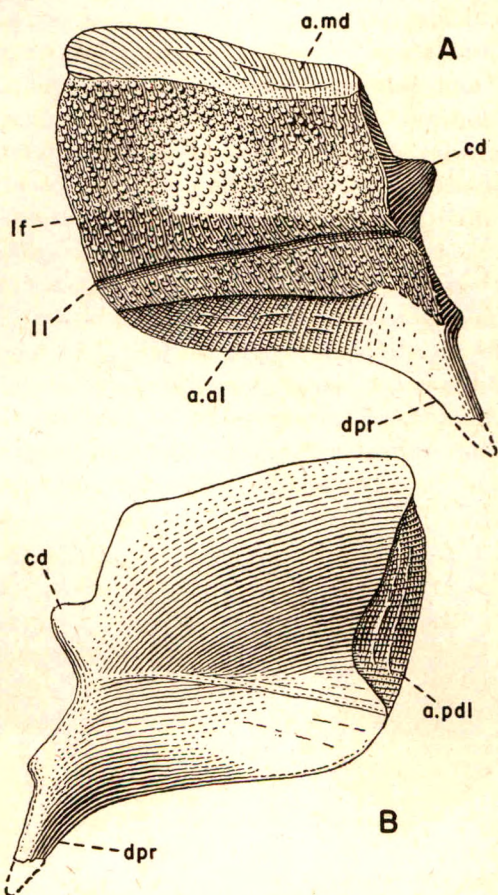


Fig. 2. Right antero-dorso-lateral plate. A. Outer surface. B. Inner surface. About size of large individual. a.al, area overlapped by AL; a.md, area overlapped by MD; a.pdl, area that overlaps PDL; cd, condylar process for paranuchal plate of cranial roof; dpr, descending process that lies inside anterior edge of AL; lf, longitudinal fold; ll, main lateral line canal.

trunk shield was broader and flatter than in the latter species.

The posterior edge, which overlaps the PDL, is relatively straight, lacking the prominent projecting angle present in *P. acadica*. The areas overlapped by MD and AL, and the area that overlaps PDL, are large and agree in most respects with those of *P. acadica*. The plate is usually flattened in preservation, but must have been bent at the line where a well-marked ridge runs antero-posteriorly (text-fig. 2A, lf); this ridge is reflected on the inner side of the plate as a longitudinal depression. Below this ridge on the external surface is a deep groove for the lateral line canal, starting just under the ridge anteriorly, and passing postero-ventrally, obliquely to the ridge. The anterior edge of the ADL is non-tuberculated and turned somewhat medially. Just above the lateral ridge and the lateral canal, it is swollen into a simple projecting condyle for the cranial roof. The anterior edge continues ventrally into a long, stout process which must have fitted into the groove near the anterior edge of the inner surface of the AL.

Postero-dorso-lateral plate (PDL) (text-fig. 3).—Two specimens of the PDL are available. UF 155 preserves an impression of the outer side lacking the postero-ventral corner, and in its counterpart an impression of the inner surface lacking the postero-dorsal corner; its maximum length is 29 mm. UF 158 shows a much smaller plate, for the most part pre-

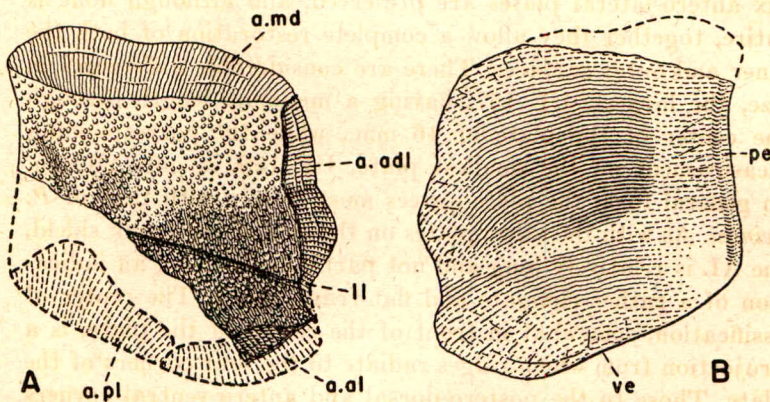


Fig. 3. Right postero-dorso-lateral plate. A. Outer surface. B. Inner surface. About size of large individual. a.adl, area overlapped by ADL; a.al, area overlapped by AL; a.md, area overlapped by MD; a.pl, area overlapped by PL; ll, main lateral line canal; pe, posterior rim; ve, ventral edge.

served as an impression of the inner side, and having a length of only 18 mm. In its proportions the PDL agrees very closely with that of *Phlyctenaspis heintzi* (Gross) and is slightly longer and narrower than in *P. acadica*. It is typical of the Phlyctenaspidae in showing no sign of the reduction posteriorly that is characteristic of most Middle and Late Devonian arthrodires. The PDL is overlapped by the four adjacent plates: the overlap area for MD is large; that for ADL agrees with *P. heintzi* (and is not indented posteriorly as in *P. acadica* where the posterior edge of ADL projects as an obtuse angle); the overlap area for AL is only partly known, and that for PL is not preserved, but both have been restored with some confidence that they are similar to those in *P. heintzi* and *P. acadica*. The outer exposed surface of PDL is marked by a groove for the lateral line canal, a continuation of that on ADL, and by a number of indistinct ridges radiating from an area in the posterior half of the plate. As preserved, the PDL is flattened, but must have been bent, as was the ADL, along a longitudinal line at about the middle of the plate. The inner surface (text-fig. 3B) shows a distinct ridge reflecting the lateral line canal, a faintly marked dorso-ventrally directed swelling in the posterior half, and a posterior slightly swollen rim.

Antero-lateral plate (AL) (text-fig. 4; plate 1, fig. 1).—Six antero-lateral plates are preserved, and although none is entire, together they allow a complete restoration of both the inner and outer surfaces. There are considerable differences in size, the largest, UF 157, having a minimum length through the center of the plate of 46 mm., while the corresponding measurement on the smallest plate, UF 158, is only 20 mm. In general form the plate agrees most closely with that of *P. heintzi*. As with the other plates on the side of the trunk shield, the AL is relatively long and not particularly deep, an indication of a rather elongate and flat trunk shield. The center of ossification, somewhat in front of the center of the plate, is a projection from which ridges radiate to the four corners of the plate. Those to the postero-dorsal and antero-ventral corners are strongly developed, while those to the other corners are ill defined. As Heintz (1933, p. 137) has pointed out, these ridges are characteristic of primitive arthrodires. The postero-dorsal corner of the AL is extended into a prominent process

overlapping the PDL and PL; this process is more extended than in *P. heintzi*, much more so than in other species of *Phlyctenaspis*, and approaches the condition found in *Arctolepis*. The postero-ventral corner of the plate is extended into a long, slender process which lies on the dorsal surface of the spine. The antero-ventral corner of the plate forms a blunt,

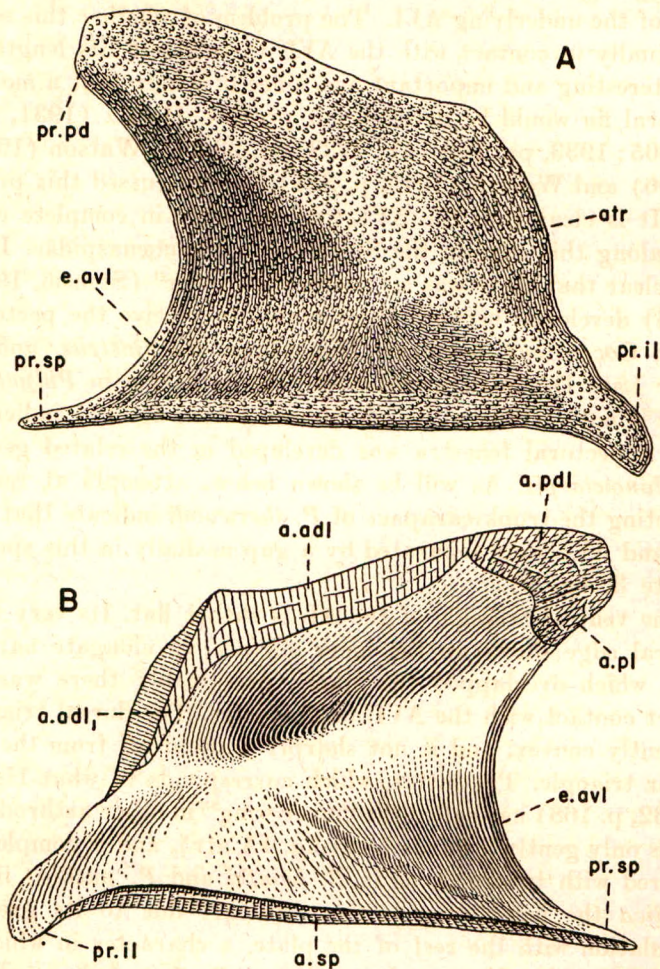


Fig. 4. Right antero-lateral plate. A. Outer surface. B. Inner surface. About size of large individual. a.adl, area that overlaps ADL; a.adl₁, area that overlaps descending process of ADL; a.pdl, area that overlaps PDL; a.pl, area that overlaps PL; a.sp, area that overlaps SP; atr, anterior triangle ("inner wing"); e.avl, posterior edge that meets AVL; pr.il, antero-ventral process for IL; pr.pd, postero-dorsal process; pr.sp, postero-ventral process for SP.

downturned process that must have curved inward over the front of the spine to meet the IL (text-fig. 4, pr. il).

The ridges from the center of ossification to the corners divide the plate into triangles. The posterior triangle has a distinctly concave surface, bounded posteriorly by a broadly curving edge that matches the curvature of the corresponding edge of the underlying AVL. The problem of whether this edge is actually in contact with the AVL throughout its length is an interesting and important one, since it is here that a mobile pectoral fin would be developed if present. Heintz (1931, pp. 304,305; 1933, pp. 140-141; 1938, pp. 23-24), Watson (1934, p. 446) and Westoll (1945, p. 384) have discussed this problem. It is clear that the AVL and AL were in complete contact along this edge in the Spitzbergen Phycænaspidae. It is also clear that there was a "pectoral fenestra" (Stensiö, 1944, p. 16) developed between these plates to receive the pectoral fin in *Coccosteus decipiens*, *Dinichthys*, *Rachioosteus*, and in other Late Devonian arthrodires. The situation in *Phlyctænaspis* is not certain, although Stensiö (*ibid.*, fig. 17) indicates that a pectoral fenestra was developed in the related genus, *Kujdanowiaspis*. As will be shown below, attempts at reconstructing the trunk carapace of *P. sherwoodi* indicate that the AL and AVL were separated by a gap medially in this species (plate 3, fig. 2).

The ventral triangle of the AL is rather flat. Its very long ventral edge shows on the inner surface an elongate narrow area which overlapped the spine; presumably there was no direct contact with the AVL on this edge. The dorsal triangle is gently convex, and is not sharply marked off from the anterior triangle. The latter, which corresponds to what Heintz (1932, p. 168) has called the "inner wing" in other arthrodires, bends only gently inwards (text-fig. 4A atr), and is completely covered with tubercles, as in *P. heintzi* and *P. pusilla*; in *P. acadica* the inner wing is more distinct due to its greater angulation with the rest of the plate, a character in which it can be considered more advanced than *P. sherwoodi*, as shown by Heintz (1933, pp. 137-138).

The inner surface of AL reflects the form of the outer surface, showing grooves to correspond to the ridges of the external face. A well-marked ridge extends from just above the center of ossification to the anterior edge of the antero-ventral

process. The areas that overlap the ADL, PDL, and PL, are as shown in text-figure 4B, except that the line between the latter two is not clearly indicated on the available specimens. The dorsal half of the anterior edge of the inner surface is depressed to receive the antero-ventral process of the ADL.

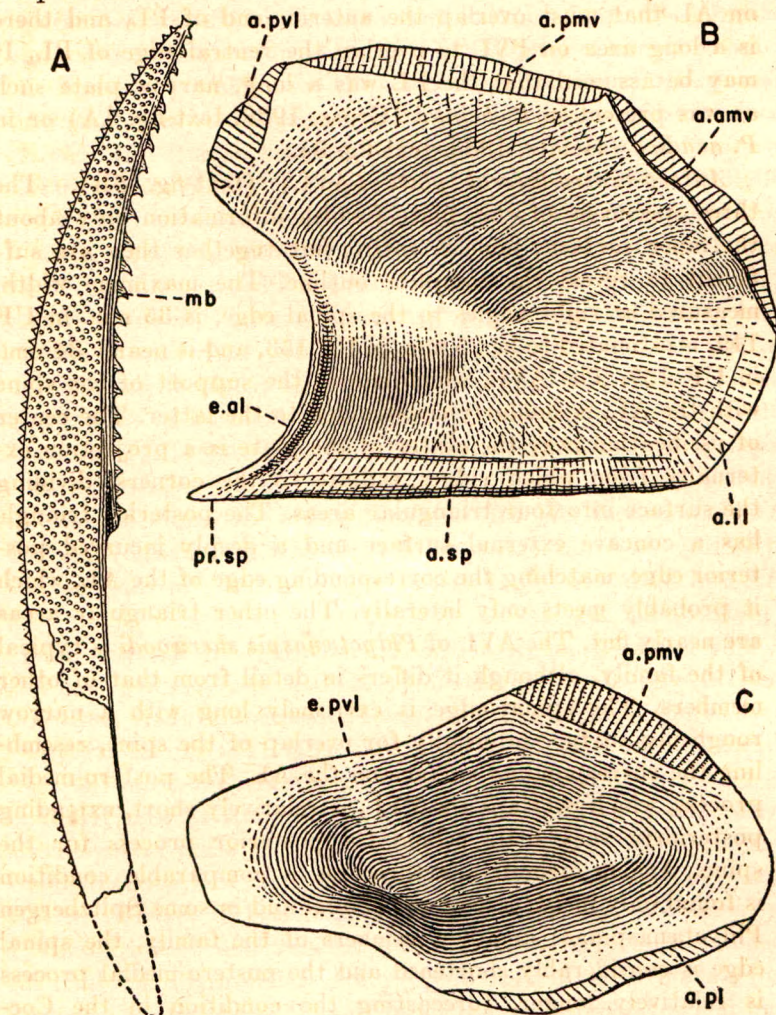


Fig. 5. A. Spinal plate. B. Right antero-ventro-lateral plate, inner surface. C. Right postero-ventro-lateral plate, inner surface. About size of large individual. a.amv, area that overlaps AMV; a.il, area that overlaps IL; a.pl, area that overlaps PL; a.pmv, area that overlaps PMV; a.pvl, area that overlaps PVL; a.sp, area that overlaps SP; e.al, posterior edge that meets AL; e.pvl, edge overlapped by left PVL; mb, barbs on medial edge of SP; pr.sp, postero-lateral process for SP.

Postero-lateral plate (PL).—No remains have been identified as belonging to this plate, but the fact that the PDL was not reduced posteriorly indicates quite certainly that the PL was also well developed. The extent of the area on PDL overlapped by PL is not known, but there is an indication of a small area on AL that must overlap the anterior end of PL, and there is a long area on PVL to overlap the ventral edge of PL. It may be assumed that the PL was a long, narrow plate such as was present in *P. heintzi* (Gross, 1938, text-fig. 1A) or in *P. acadica* (Heintz, 1933, text-fig. 3).

Antero-ventro-lateral plate (AVL) (text-fig. 5B).—The three specimens of this plate furnish information only about the inner surface; none is entire, but together they are sufficient to reveal the complete outline. The maximum width, measured at right angles to the spinal edge, is 35 mm. in UF 149, is estimated to be 25 mm. in UF 153, and is nearly 34 mm. in UF 157. The AVL, which shares the support of the spine with the AL, is similarly constructed to the latter. The center of ossification near the center of the plate is a projection externally from which ridges radiate to the corners, dividing the surface into four triangular areas. The posterior triangle has a concave external surface and a deeply incurved posterior edge, matching the corresponding edge of the AL, which it probably meets only laterally. The other triangular areas are nearly flat. The AVL of *Phlyctenaspis sherwoodi* is typical of the family, although it differs in detail from that of other members. The spinal edge is extremely long with a narrow roughened surface internally for overlap of the spine, resembling the corresponding surface on the AL. The postero-medial process, which overlaps the PVL, is relatively short, extending posteriorly very little behind the posterior process for the spine. Among primitive arthrodirea a comparable condition is found only in *Phlyctenaspis heintzi* and in some Spitzbergen *Phlyctenaspidae*; in other members of the family, the spinal edge is considerably shortened and the postero-medial process is relatively longer, forecasting the condition in the *Cocosteidae* and many more specialized arthrodirea. The anterior edge of the AVL, which overlaps the lateral half of the IL, is unusually short in *P. sherwoodi*, while the antero-medial edge for the AMV is convex and unusually long. The areas by which the AVL overlaps adjacent plates are shown on text-figure 5B as exactly as they could be determined.

Postero-ventro-lateral plate (PVL) (text-fig. 5C).—The collection contains three specimens of this plate. UF 150, with a length of 37 mm., is an impression of the inner side of a right PVL; UF 152, largely an impression of the inner side of a left PVL, has an estimated total length of 37 mm.; UF 156, belonging to the right side, is 54 mm. long; it is preserved in counterpart, largely of the inside, but showing a part of the outside of the plate. Although generally flattened in preservation, a large antero-lateral wing of the PVL was curved sharply upwards to overlap the lower edge of the PL. This wing, which is over half the length of the plate in *P. sherwoodi* and in other Phlyctenaspidae, is generally shortened and reduced, or absent, in Middle and Late Devonian arthrodiros. The presence of a long sutural surface on the inner side of the dorsal edge of this wing is a clear indication of the presence of an elongate, unreduced PL in this species.

The part of the PVL belonging to the ventral shield is nearly flat. As Gross (1937, p. 24) has emphasized, the left PVL always overlaps the right one in arthrodiros, so that the shape of the two is different, the left having a broader ventral lamina. The figure of *P. acadica* given by Heintz (1933, text-fig. 6) is incorrect in this respect.

The PVL of *P. sherwoodi* agrees quite well with that of *P. acadica* but is relatively longer and more slender, especially in the posterior part of the ventral lamina behind the lateral wing.

Postero-median-ventral plate (PMV) (text-fig. 1A; plate 1, fig. 2).—Two specimens of this plate are available, UF 157, with a total length of 46 mm., exhibiting the outer surface, and UF 158, 34 mm. long, showing the inner surface. The PMV is a flat plate, with a characterless inner surface, and with the outer surface marked particularly by the areas overlapped by the adjacent PVL's and AVL's. It agrees closely with the PMV of *P. acadica* (Heintz, 1933, text-fig. 6) and even better with that of *Prospheymaspis constricta* (Gross, 1937, text-fig. 12d).

Spinal plate (SP) (text-fig. 5A).—Remains of five spinal plates are preserved, the best of which occurs on UF 157. None of them is complete, but indicate that *P. sherwoodi* had a very long slender, gently curved SP. Its size relative to that

of the rest of the plates is not known due to the fact there is no certain association of plates of the same individual, and also because of the incomplete preservation of the proximal end which attaches to the AL and AVL. It is probable, however, that the relative length of SP and its general proportions were similar to those of *Phlyctenaspis heintzi* (see Heintz, 1937, text-fig. 8c), and it was certainly much longer and more slender than in *P. acadica*. The inner margin, anterior as far as the attachment of the AL and AVL, is set with a number of well-spaced, stout, slightly recurved barbs, and there are numerous, smaller, more closely spaced barbs on the outer margin.

The nature of the attachment of the SP to the AL and AVL is not entirely clear, but it seems quite certain that the ventral edge of AL and the lateral edge of AVL did not meet each other as stated by Heintz (1933, p. 140). It is more probable that the AL attached to the medio-dorsal edge of SP, that the AVL attached to the medio-ventral edge of SP, and that the three plates were firmly united by the endoskeletal shoulder girdle ("prespinal lamella") of which there is no trace in this species. Of the surfaces of attachment on the SP, nothing is preserved in the available material except for a notch on the medial surface for the pointed posterior process of the AL or AVL.

Antero-median-ventral plate (AMV) and *Intero-lateral plate (IL)*.—Neither of these plates has been recognized in the collection.

RESTORATION OF THE TRUNK CARAPACE

To one who has not made a special study of the group, the individual plates of the arthrodire exoskeleton have little meaning. Therefore it was considered worthwhile to attempt a reconstruction of the trunk carapace of *Phlyctenaspis sherwoodi*. The restoration proved to be difficult because there was no certain association of plates of any one individual, and also because of the wide range of size exhibited by the various plates. The procedure followed was to enlarge photographs of individual plates to fit adjacent plates of the arbitrary model size. The contours and particularly the extent of the sutural overlaps were useful in determining relative plate sizes. Composite outline drawings of the flattened plates were traced onto

perforated sheet lead, cut out, shaped in the third dimension, and assembled.

The relative sizes of the plates could be determined with considerable certainty for the most part. In the case of the PVL, the area overlapped by the AVL is so small and indistinct on the available specimens, that the posterior contour of the lateral shield had to be relied on as an indication of the length of the lateral wing of the PVL. There is no information as to the relative size of the SP, though it was clearly long, as its slender proportions indicate; it has been restored to resemble the spines of *Phlyctenaspis heintzi*, *Kujdanowiaspis podolica* and *Arctolepis decipiens*. The PL, as is pointed out above, is not represented in the collection, but must have been long and well developed judging from the direction of the posterior contour of the PDL, and the long area of overlap on the PVL. Its depth is problematical, but is restored in the model to be about the same as in *P. acadica*. The AMV and IL, which are not known, have been restored to fit the anterior and antero-medial outline of the AVL's using *P. acadica* as a guide.

During and after assembly it was found that there was little possibility of altering the general shape of the model. This is taken to mean that the model gives a reasonably certain representation of the shape of the thoracic shield, within the limits of error of the original drawings of individual plates. Of course, the shape of AMV and IL are hypothetical, and the relative size of the PL, PVL, and SP may not have been exactly as shown. The interesting problem of the pectoral fenestra was studied during the process of reconstruction. It was found that the AL and AVL may have been in contact along the lateral half of their posterior edge, but could not have met more medially; thus a pectoral fenestra must have been present in *P. sherwoodi* (plate 3, fig. 2). The size of the fenestra could have been determined more accurately if the PL had been known.

The resulting restoration (plates 2, 3) resembles the trunk carapace of *Phlyctenaspis acadica* (see Heintz, 1933, text-fig. 5) in general features, but indicates that *P. sherwoodi* had a distinctly longer and flatter shield. Its general proportions are not unlike those of *Arctolepis decipiens* (see Heintz, 1929, text-figs. 8, 9), one of the earliest of the Arthrodira.

DISCUSSION

Phlyctenaspis sherwoodi is clearly an unspecialized member of the Phlyctenaspidae as far as its trunk shield is concerned. It shows no tendencies towards the usual specializations of Middle and Late Devonian arthrodires, such as are exhibited by the contemporaneous Coccosteidae. The SP is unshortened, and the lateral wall of the trunk shield is not reduced posteriorly, retaining a wide contact with the ventral shield. The four ridges bracing the AL are characteristic of primitive Arthrodira, as is the absence of a keel on the MD. Judging by the presence of an elongate SP, it is probable that no mobile pectoral fin had been developed medial to it, in spite of the presence of a small pectoral fenestra.

The occurrence of such a primitive arthrodire in Late Devonian deposits is of great interest both from a phylogenetic and a stratigraphic point of view. The known history of arthrodires suggests that the order was originally a fresh water group, but that during the Early and Middle Devonian its members gradually moved into the seas. Finally in the Late Devonian it reached its climax in a marine environment, where a great variety of genera has been found, many of them highly specialized. In spite of this general trend within the arthrodires, a few of them continued to live in fresh water, and it is significant that for the most part these represent persistently primitive or at least slowly evolving lines. Among the few arthrodires that retained the primitive characteristics of the family Phlyctenaspidae after the close of the Early Devonian, the majority are found in continental deposits; these species are *Phlyctenaspis acadica* and *Actinolepis tuberculata* of the Middle Devonian, also *P. sherwoodi* and *Grænlendaspis mirabilis* of the Late Devonian. The Australian *Buchanosteus osseus* is the only phlyctenaspid reported from post-Early Devonian marine formations. *Coccosteus*, while advanced beyond the primitive phlyctenaspid organization, is still a long way from its specialized Late Devonian descendants, such as *Dinichthys*. Its presence in continental deposits until the Late Devonian supports the view that evolution was slower in this environment among the arthrodires. This point has considerable importance in stratigraphic studies of continental Devonian deposits where, in the absence of many invertebrates, reliance must be placed very commonly on fishes.

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A NOTE ON THE AGE OF THE TRUCKEE FORMATION

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A RECENT paper by Yen (1950) in this JOURNAL has thrown additional light on the age of the Truckee formation. His determination of a Pliocene age for these beds is substantiated by recently discovered vertebrate evidence. As a supplement to Dr. Yen's interesting paper the following note is submitted.

Since its description by King (1878, pp. 109-115) nearly seventy-five years ago, there has been constant speculation on the age of the Truckee formation. King determined the age of these beds to be Miocene on the basis of a rhinoceros tooth and a collection of fresh water mollusks. This material was collected near the type locality in the Kawsoh, now Hot Springs, Mountains in Churchill County, Nevada.

Buwalda (1914) described a fragmentary gomphotheriid tooth from beds assigned to this formation from a locality near Verdi, Nevada. He reviewed the literature on the Truckee formation and decided that the beds were either Middle or Upper Miocene in age. The presence of the proboscidean tooth was the basis for his decision on the lower limit of the formation's age. The upper limit was based on his estimate of the time required for the completion of the diastrophism, vulcanism and erosion that occurred in post-Truckee times.

Buwalda then correlated these beds with the Esmeralda formation in the Fish Lake Valley region. It was not known at that time that the Esmeralda formation contained two distinct faunas. One is the Stewart Spring fauna, composed of re-worked Miocene remains, and the other, the Fish Lake Valley fauna, which is composed of Lower Pliocene forms. This separation was established by Stirton in 1932.

In his review of the Miocene and Pliocene faunas of Nevada, Stirton (1939a) pointed out that the tooth described by Buwalda closely resembled ?*Trilophodon simpsoni* Stirton (1939b) from the Lower Pliocene of the San Francisco Bay region. He further stated that a fragmentary horse metacarpal from the Truckee beds near Hazen, Nevada, indicated a Lower or Middle Pliocene state of development.

In 1948, a field party from the University of California was fortunate enough to collect a large mammalian fauna from the

Truckee formation just ten miles north of U. S. Highway 40 on the Brady Hot Springs-Nightingale Road. The presence of fossil bones at this locality was reported by Mr. R. E. Brady to Dr. V. P. Gianella at the University of Nevada. This locality, which has been designated as the Brady Pocket (Macdonald, in press), contains an unusually large concentration of fossilized remains in contrast to the usual situation in Tertiary deposits in this region.

Of primary importance is the presence of a number of *Eucastor lecontei* (Merriam) teeth and a maxillary of *Osteoborus diabloensis* Richey. These species are typical of the Clarendonian Black Hawk Ranch fauna (Stirton, 1939b; Richey, 1938, 1948; Macdonald, 1948) and indicate a late Lower Pliocene age for this assemblage.

The correlation of Nevada Tertiary deposits is extremely complicated by the rapid lateral changes in lithology, the heavy blanket of pediments, the discontinuity of formations caused by the basin-range faulting, and the paucity of fossil remains. It is therefore entirely possible that the Truckee formation may transgress several temporal boundaries, and that the exposures from which identifiable fossils have been collected are of different ages. Plant and animal remains have been recorded from the type locality in the Hot Springs Mountains, Hazen, Verdi and from the Brady Pocket. Each of these occurrences may represent a slightly different portion of geologic time. But, in spite of this possibility, it seems best that we date the formation on the basis of the most positive evidence and designate it as late Clarendonian in age.

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MUSEUM OF GEOLOGY

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REVIEWS

Worlds in Collision; by IMMANUEL VELIKOVSKY. Pp. xiv, 401. New York, 1950 (The Macmillan Company,¹ \$4.50).—The publishing company sent to this JOURNAL a copy of Velikovsky's book, with a request that we review it, presumably after full scientific appraisal such as our reviewers are accustomed to give. Since the author's thesis, that a great comet made two close contacts with Earth about 1500 B.C., purports to rest on human records, students of ancient history and of prehistory are required, in addition to scientists, for a fair appraisal.

Dr. K. S. Latourette, Professor of Missions and Oriental History at Yale University, comments as follows:

"In his preface the author rightly declares that 'laws must conform with historical facts, not facts with laws.' When this test is applied his startling conclusions fare badly. He has combed an amazing range of historical records for evidence to corroborate his thesis. However, he has failed to apply to these records the principles for determining what truth lies back of them—principles which competent historians have learned to regard as the elementary and essential tools of their craft. For China, on whose voluminous literature he rests much of his case, he is quite unaware of the findings of recent scholarship and depends chiefly upon Occidental authors who, although eminent in their day, have now been largely superseded. He makes frequent, and in one place, extended mention of the Emperor Yao (whom he generally calls Yahan), treating him as historical and the accounts of him as authentic, whereas no present-day expert in Chinese history would accept without question what has come down to us about him, and most of them would either doubt whether he ever lived or would declare that we can say nothing about him with assurance. To take another example of many that might be cited, in the account of the happenings on Mt. Sinai during the Exodus, quotations are brought together from authors of a number of different centuries, usually with no effort to determine whether the events they are said to describe can be shown to belong to the same period, and with no apparent attempt to evaluate the writers' accuracy."

Velikovsky gives prominent place to his interpretation of records concerning ancient America. Dr. George Kubler, Professor of the History of Art at Yale and a recognized student of Mesoamerican civilization, gives the following analysis:

"The postulates are as follows. A comet appeared between 2000 and 1000 B.C., and 'twice made contact with the earth' in mid-millennium at an interval of 52 years. The same comet assumed circular orbit as the planet Venus between the tenth and eighth

¹ Publication now in hands of The Doubleday Co.

centuries B.C. Great disturbances in the earth and its atmosphere occurred in both epochs. In the eighth century B.C., the calendars of the peoples of the world were reformed to match the changed length of the solar year, which was but 360 days between 1500 B.C. and the eighth century. The nature of the great disturbances were recorded by witnesses and transmitted to posterity in many forms of writing and storytelling.

"Ancient American sources, and sources about ancient Americans, are used by the author as essential proofs of the global character of the events, and of the interval between 'contacts' *ca.* 1500 B.C. The 52-year Mesoamerican cycle is taken as an historical survival of the terrors experienced between the two 'contacts' of the Venus-comet with earth. The Old Testament does not give the author an accurate measure of the interval; the Mesoamerican 52-year cycle serves this purpose. The 52-year cycle of the Mayas and Mexicans consisted of 18,980 days, or 52 periods of 365 days. But the 52-year interval, by hypothesis, originated before the solar year settled down to its present length, so that the Mexicans and Mayas *ca.* 1500 B.C. are now proved to have had proleptic knowledge of the state the solar system was to assume after the eighth century B.C.!

"Similarly, the author lays great value upon the Mexican New Year date as February 26, Old Style. His source here is a Jesuit, Father Acosta, who wrote *ca.* 1589. Acosta's source in turn was Juan de Tovar, writing *ca.* 1585. These two writers stand alone in saying that the Mexican year began on February 26. The list below gives other New Year days for the Mexican calendar from equally reputable sources.

- February 1 (Sahagun, Torquemada)
- 2 (Sahagun, Hernandez)
- 24 (Codices Telleriano-Remensis; Vaticanus 8788)
- 26 (Tovar, Acosta)
- 27 (Pedro de San Buenaventura)
- March 1 (Motolinia)
- 2 (Guevara)
- 10 (Serna, Leon)
- 20 (Ixtlilxochitl, Duran)

The Maya New Year Day, according to Landa, fell on July 16. Other dates as well are suggested by the sources: July 18 and July 15. Many isolated communities in Mesoamerica today still retain the ancient year of nineteen months. December, January, and May are all actual New Year months, and probably go back to ancient observances, of which the origin relates to climatic and hydrographic conditions in a given area.

"To return to the 52-year cycle—its period of 18,980 days arises from the combination of two smaller cycles. The first is a ritual calendar of 260 days formed of 20 day names and a 'week' of 13 numbered positions. The second is the year of 365 days, divided in 18 months of 20 days each, plus a nineteenth month of 5 days. No day and month name with stated coefficients can therefore recur for 18,980 days, since the least common multiple of 260 and 365 is $5 \times 52 \times 73$. Morley assigns the invention of this calendar, on internal evidence, to a date not earlier than the fourth century B.C. The 52-year calendar originated by arithmetical requirements; there is no evidence that the 52-year period commemorates anything.

A glance at the present state of archaeological knowledge about early American peoples will be useful. In 1500 B.C. the American Indians everywhere were engaged in the invention of agriculture and in early village life. There was no writing, no exact calendar, and no social organization beyond village life. Conditions in the eighth century were little different. The Mesoamerican cosmology to which Velikovsky repeatedly appeals for proof did not originate and could not originate until the beginning of our era. Velikovsky alludes to 'Toltec-Aztec' wars as possibly occurring 'before the present era.' Historically, Toltec is to Aztec approximately as Republican Rome is to Byzantium. Toltec remains in Mexico and the Maya area are now dated before 1260 A.D. Aztec civilization is now dated after 1360 A.D."

Since the astronomer is entitled to a hearing in cosmic matters, we turn now to the reactions of Professor Rupert Wildt, of the Yale Observatory:

"By a merciful ordination of the economic system under which we live, the host of amateur cosmologists seldom command the means of bringing their speculations before the eyes and ears of the world. The author of the book under review has scored over his brethren in two respects. He has found a publisher eager to promote the sale of his opus by the sort of publicity commonly reserved for the more florid contemporary fiction. But his real coup had been to launch in the Scripta Academica Hierosolymitana a kind of *Prolegomena* bearing the quaint title of '*Cosmos without Gravitation*' (New York—Jerusalem, 1946). This pamphlet, termed a Scientific Report, looked rather odd in a series of publications to which Albert Einstein and other eminent mathematicians and physicists had contributed. There and then Velikovsky criticized Newtonian mechanics with an incredible naïveté, pronounced it to be a failure, and offered equally naïve suggestions how to construct an electromagnetic theory of gravitation. A measure of Velikovsky as a student of the physical sciences may be gained by pondering his acute observation that 'clouds and mist are composed of droplets

which defy gravitation' (*Cosmos without Gravitation*, p. 4). His budget of gravitational paradoxes contains twenty-four more items, many of which reveal a similar degree of penetration into the mysteries of terrestrial and cosmic physics. Velikovsky's fellow contributors to the Scripta Academica seem to have resigned themselves to his company. At any rate, there is no indication that they took any notice of him.

"No useful purpose would be served by summarizing here Velikovsky's 'evidence' for the series of cosmic catastrophes that he supposes to have occurred between 1500 and 700 B.C. The crucial point is that Velikovsky, in effect, repudiates his earlier rejection of Newton: 'The theory of cosmic catastrophism can, if required to do so, conform with the celestial mechanics of Newton' (*Worlds in Collision*, p. 884). But the readers of the book are spared the realization that its author ever professed belief in what he called 'the empiric evidences of the fallacy of the law of gravitation' (*Cosmos without Gravitation*, p. 11). We look in vain for an explanation of what possessed the man between 1946 and 1950 and cannot help wondering—is this a case of individual amnesia overtaking the author, or does he have so little respect for scientific critics as to rely on their collective amnesia? Let us take the charitable view and assume that he is so fascinated by his visions of cosmic catastrophes as to have lost sight of everything else: he is even ready to reinstate Newton! But then he must bow to the verdict of celestial mechanics, namely that his 1950 claim quoted before is demonstrably wrong; for astronomers can trace back the planetary orbits for hundreds of thousands of years, and there is no evidence whatever of a close encounter of the Earth with either Mars or Venus, as postulated by Velikovsky. Moreover, his idea of a physical similarity of the massive planet Venus with such an 'airy nothing' as a comet is simply absurd; even the most massive of comets amounts to less than one-millionth of the mass of Venus.

"To sum up, modern celestial mechanics does not offer any support to Velikovsky's speculations on cosmic catastrophes. Certain subsidiary arguments, which he culled from astronomical texts of Mesopotamia and Egypt, can be left to the historians of science to deal with. Conspicuous by its absence from the book that parades so much learning is the name of the greatest living authority on Babylonian and Egyptian astronomy, Professor O. Neugebauer, of Brown University."

In common with other scientists who may have examined the book, the geologist is both amused and appalled by the ideas and the methods of Dr. Velikovsky. Two examples will serve as a measure of his competence in geologic matters.

In discussing the origin of petroleum he lists two theories—the

inorganic and the organic—but does not go on to inform the reader that to modern students of the subject the inorganic theory has historical interest only. An immense accumulation of factual evidence, won from intensive studies of oil fields throughout the world, of sediments now accumulating under diverse conditions, and of the chemistry of organic materials, indicates convincingly that oil and natural gas have been distilled slowly, during the long history of the Earth, from remains of plants and animals deposited with muds and oozes, chiefly on ancient sea floors. Velikovsky, either in complete ignorance or with cavalier disregard of all evidence, blandly states that the elements carbon and hydrogen in the tail of his comet combined and rained down on the Earth within human history, to form our present wealth of petroleum. A single elementary consideration reveals the utter absurdity of this suggestion. Because oil is much lighter than water, oil accumulations can exist underground only in natural “traps” that are covered by layers of impervious rock material such as clay or claystone. Probably Velikovsky would see no problem in having his rain of oil from the comet percolate thousands of feet deep into bedrock, against the resistance of ground water and through layers so impenetrable that they now restrain the oil from rising again. Perhaps the laws of permeation, like the laws of gravitation and of mechanics in general, were somehow suspended while the comic bodies disported themselves!

Velikovsky raises anew the matter of “erratic blocks”—masses of rock that clearly have been displaced through distances of tens or even hundreds of miles from the localities of their origin. No problem that has confronted geologists seems to be more convincingly solved than this one. The “erratics” occur only in areas that are known, on independent evidence, to have been covered with glacier ice in the geologic past. Study of existing glaciers—in high mountains, in Greenland, in Antarctica—demonstrates that ice is now transporting masses of rock that are in every way comparable to the older “erratics.” Every essential link from effect to cause has been adequately supplied, in the judgment of informed students. But the author of *Worlds in Collision* finds of no account the mass of evidence accumulated through more than a century of scientific effort. He wants the “erratics” as witnesses to a gigantic tide that swept the lands during his cosmic catastrophe. How the effective tide was restricted to those land areas that now preserve clear marks of former glaciation he does not offer to explain. Without hesitation he sweeps into discard the results of critical research during several generations, and then, unhampered by any embarrassing facts, he rushes in with his own grandiose speculation. All but Velikovsky are out of step!

And why, readers may well ask, should a scientific journal give the least attention to such patent nonsense? Frankly, our chief concern is to focus attention on the publisher, rather than on the book or the author. But doesn't a publishing house have the right to print any kind of literature that comes within legal bounds? Yes, so long as the literature is represented for what it is. The Macmillan spring catalogue lists the Velikovsky book under the heading "Science" along with four other books whose titles suggest that they may be properly classified. The four authors must feel much flattered at finding themselves in company so distinguished!

We are given advance notice that *Worlds in Collision* is to be followed shortly by more of the same kind. Under what appropriate heading shall we advise that the publisher classify, in future, works that do not rise to the level of good science fiction, and are best described as burlesque of both science and history? If we are to judge from the tactics employed in advertising the subject of this review, its publisher is concerned chiefly with the classification "best seller."

CHESTER R. LONGWELL

Structural Petrology of Deformed Rocks; by H. W. FAIRBAIRN (with supplementary chapters on Statistical Analysis, by F. Chayes). 344 pp. Cambridge, Mass., 1949 (Addison-Wesley, \$12.50).—The second edition of Professor Fairbairn's book will be welcomed by all workers in the field of structural petrology. It is well printed and abundantly illustrated with clear line drawings; and orthodox binding renders it much more attractive than its loosely bound predecessor. The general scope of the book, and the method of independent treatment of established facts, interpretation of these, and technique of petrofabric analysis, are the same as in the first edition. But there is a considerable amount of new material, drawn mainly from recent literature written in the English language. In Part I (established facts) there are new data on orientation of olivine in peridotites, on deformation lamellae in quartz, and on preferred orientation of deformed ooids and pebbles in meta-sediments. New material in Part II (interpretation and hypothesis) includes "additional examples of microfractures and multiple s -surfaces, a summary of rotation and relative movement of fabric elements, an account of recent regional investigations, and a separate chapter on the problem of tectonic transport." Part III (technique) has been expanded by adding a brief description of the interference-figure method of determining the orientation of optic axes in grains of uniaxial minerals (useful especially in deformed marbles), and by including details of additional x-ray techniques. The two concluding chapters, on statistical treatment of petrofabric data, have been written by Dr. F. Chayes.

Fairbairn's *Structural Petrology of Deformed Rocks* is the most up-to-date and probably the most satisfactory presentation of this subject that has yet appeared in English. Moreover it is excellently illustrated and has a good bibliography. But it has a number of defects, the more serious of which are noted below in the hope that they may be remedied in the next edition.

The data of structural petrology are gathered by intricate and time-consuming techniques, and their interpretation is based on concepts that are imperfectly understood by, or unfamiliar to, many petrologists. Simplicity and clarity of writing is therefore essential in any comprehensive treatment of the subject. In the reviewer's opinion Professor Fairbairn's writing at times lacks clarity and may even be ambiguous. For example, the statement on p. 88 "Olivine . . . shows high concentration of (010) parallel to the banding, with no directional orientation of (010) . . ." does not clearly convey what the reviewer presumes is the actual meaning: namely that there is no preferred orientation of any crystallographic direction lying in (010). The same ambiguous term "directional orientation" applied to crystal planes appears elsewhere in the book. Again on p. 17, it is said that "undulatory extinction bands in tectonite quartz are almost invariably parallel to the crystal axes"—instead of to the axis [0001]. In a paragraph dealing with the *b* axis of tectonite fabrics (p. 6) it is not clear whether *b*, or the lineation, is referred to as being "commonly perpendicular to *a*" (and hence, by implication, occasionally not perpendicular to *a*). There are numerous references (*e.g.*, p. 25; line 2; captions to figs. 2-24 to 2-28, 8-5, 8-6) to orientation data for lamellae and optic axes for calcite grains with "(01 $\bar{1}$ 2) twins." These actually refer to grains recorded in the original accounts of Sander and others as showing (01 $\bar{1}$ 2) lamellae due to twinning or to some other mechanism (*e.g.*, translation gliding). The statement in the middle paragraph of p. 269 regarding measurement of (01 $\bar{1}$ 2) lamellae in calcite actually is true only of sections mounted between hemispheres of appropriate refractive index (1.65 $\pm$). Moreover the opening sentence of the last paragraph on p. 269 (referring to "high relief characteristic of carbonates") is obscure if not meaningless, and is inconsistent with the value of refractive index (1.529) given later for light vibrating normal to (01 $\bar{1}$ 2) lamellae. The use of the word "anachronistic" in the fourth paragraph of p. 226 is singularly inappropriate, and can only confuse the reader. Other instances of confused writing could be cited.

Misprinted or misused crystallographic symbols are too numerous. For the reader's benefit the following corrections are noted: p. 9, table 2-1, tourmaline: (0001) should read [0001].

- p. 9, table 2-1, footnote 2: $(0\bar{1}\bar{1})$ should read $(10\bar{1})$.
- p. 88, line 28: $[001]$ should read $[100]$.
- p. 88, line 29: (010) should read $[001]$.
- p. 88, fig. 2-44: $[100]$ should read $[010]$.
- p. 86, fig. 2-51: 010 should read (010) .
- p. 119, table 9-1, footnote r : $(0\bar{1}\bar{1})$ should read $(10\bar{1})$.
- p. 139, fig. 10-5, lines 2, 3: $(02\bar{1})$ should read $(02\bar{2})$.
- p. 140, line 21: $(10\bar{1}2)$ should read $(\bar{1}012)$.
- p. 140, lines 28, 24: $(20\bar{2})$ should read $(\bar{2}02)$.

The standard use of different types of brackets to distinguish crystal faces, *e.g.*, $(10\bar{1})$, $(\bar{1}10)$ from corresponding forms, *e.g.*, $\{10\bar{1}\}$ is now so well established that it should be followed in books such as this.

Dr. Chayes has called the reviewer's attention to several misprints in the last two chapters:

- p. 299, table 22-1, caption: 2-15 should read 16.
- p. 300, line 25: 180 should read 181.
- p. 301, table 22-2, caption: 180 should read 181.
- p. 302, fig. 22-1, caption: 180 should read 181.
- p. 315, table 28-2, footnote: X^2 should read chi-square.
- p. 315, line 7: section 7 should read section 6.
- p. 318, equation 28-18: denominator of the left-hand factor should read $(n-1) S_n S_y$.
- p. 321, heading, last section: 6 should read 7.
- p. 325, heading, line 5: 7 should read 8.

The section (pp. 257-270) dealing with universal-stage procedures in petrofabric analysis would be improved by omitting descriptions of standard methods for determining optic orientation of uniaxial and biaxial crystals in general. No student should attempt petrofabric analysis until he is familiar with such routine measurements, descriptions of which are available in a number of standard works. But it would be useful to have special instructions for work on those minerals commonly investigated in petrofabric analyses—quartz, calcite, dolomite, feldspars, micas, hornblende. Each presents special problems that can be solved by particular means. In dealing with quartz, for example, there is the special problem of distinguishing a positive uniaxial mineral (quartz) from a mineral with high axial angle (feldspar); and this can be done much more rapidly than general distinction of any uniaxial from any biaxial crystal. Calcite of deformed rocks presents difficulties arising from its extreme birefringence and from close spacing of deformation lamellae. In measuring cleavage in biotite and hornblende certain positions, in which light absorption

is minimal, are preferable to others where absorption is strong. It would be useful for students to have the benefit of Professor Fairbairn's experience in connection with such special cases as these.

The two final chapters on statistical analysis of fabric diagrams are clearly written, but are somewhat out of place in a book dealing with fabric of deformed rocks. As stated by Dr. Chayes on p. 297, the question of whether the pattern of an orientation diagram is significant or fortuitous seldom arises in connection with the fabric of deformed rocks. It does arise in the case of some sedimentary and igneous fabrics; but these are beyond the scope of the book. To the reviewer, the most satisfactory test of the reality or significance of a weak orientation pattern is comparison of two diagrams based on two different sets of measurements made on the same fabric. One of the advantages of petrofabric as compared with certain other statistical studies is the ease with which a second set of data can be obtained when such checking becomes necessary.

The criticisms offered above are intended to be constructive. In spite of the defects mentioned, Professor Fairbairn's book is one that should be read by every petrologist, and should be continuously available to every student of the fabric of deformed rocks.

F. J. TURNER

Earth Waves; by L. DON LEET. Harvard Monographs in Applied Science, No. 2. Pp. 122; 58 figs. Cambridge, Mass., and New York, N. Y., 1950 (Harvard University Press, John Wiley & Sons, Inc., \$8.00).—This book is a revision and extension of a series of eight lectures on "Applications of Seismological Techniques to Engineering Problems," given before the Lowell Institute of Boston in 1946 by Professor Leet. The work is directed to the reader with a general background in physics, geology or engineering, rather than to the specialist. Accordingly, the necessary mathematical developments have been kept very simple, and are very clearly presented.

The first chapter describes briefly some modern types of seismographs, after an account of simple harmonic motion and forced vibrations. Chapter II gives a strikingly clear and distinct account of the observed types of earth waves. A third chapter, "The Transmission of Earth Waves," occupies nearly half of the book. Here the interpretation of travel-time graphs is considered at length, and is applied briefly to earthquakes, and in more detail to seismic prospecting. Several illustrations of structural mapping are explained. A short final chapter treats microseisms, and the problem of the location of storm centers from seismic observations.

This monograph should prove of much value in supplying a modern survey of applied seismology to a wider audience than is served by the technical periodicals.

JOSEPH ASHBROOK

American Journal of Science

SEPTEMBER 1950

THE CHEMICAL KINETICS OF THE KATMAI ERUPTION¹

C. N. FENNER²

PART I

ABSTRACT. In papers published several years ago, I gave a description of the pumices ejected in the great eruption of Mount Katmai in 1912. These pumices, in innumerable specimens, show remarkable associations of contrasting felsitic and mafic material, an effect that was ascribed to the assimilation of basic rocks by the new siliceous magma. This view aroused skepticism among geologists as to whether assimilation on such a large scale were credible.

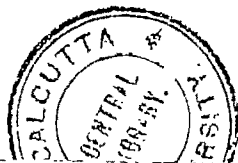
In the present article the possibilities of exothermic reactions in the magma are explored, and the large quantities of heat that may be developed are indicated. This conclusion is based upon well-recognized chemical principles, but whatever might be deduced in this manner, the real basis for conclusions is preeminently the pumices themselves. Therefore, the greater part of the present paper is devoted to detailed descriptions of their field relations, their petrography, and their chemistry, from every relevant standpoint. Most of the evidence presented is new. It points directly and unmistakably to the assimilation of great quantities of basic rock by the new magma.

The phenomena are different in kind and in magnitude from effects that have been described in other volcanic eruptions. Because of this and because the Katmai region is so difficult of access for study by geologists, descriptions will be given in rather more detail than is usually required.

OCCASIONALLY there appears in discussions among geologists an attitude that seems rather like a protest against the use of physico-chemical arguments to support views of magmatic processes. Probably this attitude is not widespread, and it may be disappearing, but there seem to be definite traces of it still. The implication is that the principles and methods of physical chemistry are so far out of the field of the average geologist that he is unable to judge of their

¹This work is based largely on studies carried out by the author at the Geophysical Laboratory during his years there as a member of the staff.

²Dr. Fenner completed this paper shortly before his death in December, 1949, and arranged to have the manuscript forwarded to Dr. A. Knopf, for reading and submission to this Journal.—*The Editor.*



merits and feels helpless in offering a purely geological observation. As the present considerable physico-chemical reasoning (character), it may be desirable as an introduction for what follows to inquire for a moment at the protest.

We can probably agree that anyone who applies principles of physical chemistry to geology and interprets results in terms with which geologists are unfamiliar. Above all, everyone should recognize that the application is valid only so far as they agree with geological principles. This is vital. It is in this respect that geological principles cause for dissatisfaction. There has been considerable work by chemists and physicists who have tackled problems which geologists have not always recognized the value and truth of. The blunder of underestimating the age of the Earth, and there was no escape from his conclusions, is a good example. In other instances, writers have disregarded geological views but have shown that they are familiar with well-established geological relations. To explain all tectonic movements of the Earth, static loading and unloading come to mind.

Now let us look at the other side of the coin.

If geologists are not familiar with the principles of physical chemistry in their application to geology, they are remiss in not availing themselves of important methods. They have found these methods of immense value in their own industry is founded upon them. An igneous rock, for example, else it may be, is certainly a chemical compound. The general laws of physical chemistry apply. In solution, differing from anything with which geologists have dealt, originating in the depth of the Earth, removed from direct observation and undergoing chemical and physical changes in its ascent. Any logical means of attack to solve its mysteries is welcomed, provided always that there is agreement with observations.

Physical chemistry is not a new development proposed upon geologists before they have had time to develop its principles. Its roots go back more than

and are involved in general knowledge of chemistry and physics. Its more direct development may perhaps be associated with the formulation of the law of mass action by Guldberg and Waag  in 1867. This stated in quantitative terms that the advance toward completeness of a chemical reaction is proportional to the concentration of the substances reacting. In 1878 Raoult's important paper on the depression of the freezing points of liquids by the presence of dissolved substances was published. At about this same time Willard Gibbs first enunciated the phase rule, but in a form so clothed with abstruse mathematics that it was not until 1887 that Roozeboom disclosed the fundamental importance of this great generalization.

It was in 1887 also that Svante Arrhenius ascribed electrolytic conductivity to ionic dissociation. Van't Hoff applied this to a determination of the proportionality between the number of ions and the osmotic pressure that they exert, as well as their influence in raising the boiling point and depressing the freezing point of electrolytic solutions.

The principles of thermodynamics, which are the basis of much of physical chemistry, were introduced in their modern form by Clausius in 1850, but it was in the 1880's and 1890's that they were most actively developed in the manner that associated the course of chemical reactions with the quantity of heat evolved and the maximum work obtainable in reversible reactions. Much of this mathematical treatment was essentially the application of the second law of thermodynamics. On this basis quantitative relationships were established and the science of physical chemistry experienced a rapid growth. Many workers, experimental and theoretical, were important contributors, but La Chatelier, van't Hoff, Roozeboom, and van der Waals were outstanding for their multifarious activities.

In the United States, full appreciation of these developments, even among chemists, appears not to have occurred before the late 1890's or early 1900's. Then the teaching of chemistry became revolutionized.

How did geologists react to this new and powerful instrument placed at their disposal? In general, the effect was hardly perceptible for a long time. There were only isolated attempts to incorporate these principles in geologic teaching. As far back as 1861 Bunsen had introduced the idea that a magma is a

solution, and he thus explained that the separation of minerals on cooling is not in the order of their infusibility. In 1892 Barus and Iddings had found that magmas are electric conductors, which leads to the important conception that, to a greater or lesser degree, their constituents are ionized. This and other principles that had been lately developed dealt a heavy blow, not well recognized at the time, to the then-prevalent view that the nature of the compounds existing in a magma could be deduced on the theory of a selective and all-powerful chemical affinity, which decides what combinations take place in the solution and which manifests itself likewise in the minerals crystallizing out. Traces of this idea still survive. Undoubtedly there is a powerful chemical force involved, which may be called affinity, but it is only one of several important factors in determining what combinations shall be formed.

At about this era Vogt and Tammann did very important pioneer work in the application of the newer ideas of geology. Others might be mentioned, but the purpose is merely to raise the question why geologists have not taken advantage of methods of attack made available to them. One might suppose that at this period or a little later the newer chemical ideas would have permeated college atmospheres sufficiently so that students taking advanced training in geology would have become exposed to them by collateral association at least, and would have recognized their value and have taken means to add them to their equipment. Until recently, only a few appear to have thus availed themselves.

In the U. S. Geological Survey the influence of Barus, Becker, and Iddings can be recognized in the establishment, in 1905, of an experimental laboratory. In 1907 this was made the nucleus of a new organization, the Geophysical Laboratory of the Carnegie Institution of Washington.

The importance of the work of the Geophysical Laboratory was recognized almost at once and was hailed with great appreciation, but though its researches have now continued for more than 40 years, the effect upon geological thought has not been quite what might have been hoped for and expected. The importance of its work should have been recognized as lying not only in the experimental results obtained but also in bringing to bear upon geological problems a new method of attack involving a new conception of the properties of magmatic solu-

tions and their products. Petrologists in particular might well have recognized a stimulus to take up a study of the principles of physical chemistry so that this training might become incorporated in their own mental discipline.

The geological interpretation and application of experimental results and of field and microscopic observations in physico-chemical terms should not be regarded as something to be left to a few specialists. The ability to make such interpretations should be part of the equipment of all students of igneous and metamorphic phenomena.

THE LAW OF MASS ACTION

The law of mass action is one of the fundamental tenets of modern chemistry. The law applies primarily to equilibria in homogeneous systems, such as a gas mixture or a liquid solution. With modification it applies to reactions that result in heterogeneous phases, such as the precipitation of a solid or the evolution of a gas from a solution.

Long ago Berthollet observed that the concentration of reactants often determines whether a given reaction or its reverse takes place. In this way may be explained why a chemical change may fail to become complete and may come to a halt before the reactants have been entirely transformed. The forward reaction transforms the reactants A and B into the resultants A^1 and B^1 , but is accompanied by a reverse reaction which transforms A^1 and B^1 into A and B. At the halting point each reaction offsets the other. The resulting chemical equilibrium is commonly written $A+B \rightleftharpoons A^1+B^1$.

W. Nernst (1904, p. 432) states: "The genuine kernel of Berthollet's idea is today the guiding principle of the doctrine of affinity. This holds good especially for the conception regarding many reactions that proceed to a completion, i.e., until the reacting substances are all used up; but only for this reason, viz., that one or more of the products of the reaction either crystallize out or evaporate off, and hence the reverse reaction becomes impossible."

Guldberg and Waag , in 1867, interpreted this condition by assuming that the state of equilibrium attained in a reversible reaction is the result of the speeds of the two opposed reactions, for each of which the velocity V or V^1 can be expressed in terms of a constant multiplied by the *concentrations of the reacting substances*.

Following out the logical consequences of this assumption, they derived a formula for a constant of mass action that expresses these relations in a comparatively simple form.

To represent a reversible chemical reaction we may write the equation $m\text{A} + n\text{B} \rightleftharpoons m^1\text{A}^1 + n^1\text{B}^1$. Here m mols of A and n mols of B unite to form m^1 mols of A^1 and n^1 mols of B^1 . When these substances have reached equilibrium, reactions proceed in either direction. Then, for K (the constant of mass action for any specific set of reactions) we have

$$K = \frac{\text{conc } \text{A}^1 m^1 \times \text{conc } \text{B}^1 n^1}{\text{conc } \text{A} m \times \text{conc } \text{B} n}$$

By determining K for any given concentration, the same K is applicable for any other concentration (at the same temperature).

There are two closely related principles on which the law is based. These are the kinetic state of the solution and the reversibility of reactions.

In any fluid, gaseous or liquid, the chemical units—molecular, associated molecular, ionic, etc.—are believed to be in violent agitation, however tranquil the fluid may appear to ordinary observation. Unless viscosity restrains the range of action, they move with great speed in all directions, battering each other and the walls of the vessel in almost infinite collisions. This is simply the classical kinetic theory of matter—the theory that the particles are all in vigorous motion and that this motion is heat, and that absolute temperature is proportional to the average kinetic energy of the particles.

When we apply this conception to chemical solution of several components, a new idea enters. The impact of collisions results in chemical reactions. There is incessant breaking down and regrouping of the chemical units. Obviously, any particular kind of unit undergoes destructive impacts by units of other kinds in proportion to the concentrations of the latter, but its resistance to destruction depends on the strength of the bonds of “chemical affinity” between its atomic constituents. Thus, both concentration of reactants and chemical affinity are factors in determining in which direction reactions proceed. Even at equilibrium there is a constantly active process that brings about an exchange of partners between compounds, a breaking up of molecules into ions, and a union of simple molecules into associated molecules—all the sorts of reactions

that chemistry recognizes. If such a system is isolated from outside influences, the agitation and its accompanying reactions will reach an equilibrium in which it will persist indefinitely. This is a statistical equilibrium and does not imply a cessation of reactions. If the concentration of one of the reactants is increased or diminished, the effect proceeds throughout the system to a new statistical equilibrium.

Many useful applications of the law of mass action have been made by chemists, but in such a complex solution as an igneous magma, in which even the nature of many of the compounds that may be formed is unknown, such a quantitative application is impossible. Nevertheless, important deductions may be made, based simply on the concepts of the law.

We may regard an igneous magma as composed of innumerable combinations of the positive ions Al^{+++} , Fe^{++} , Fe^{+++} , Mg^{++} , Ca^{++} , Ba^{++} , Sr^{++} , Mn^{++} , Na^+ , K^+ , and H^+ , and the negative ions SiO^{-4} , S^{-2} , SO_4^{-2} , Cl^- , F^- , O^{-2} , OH^- , and others that are present in minor quantity. Having in mind the evanescent character of some of the products that are likely to result from the thermal battering that they undergo, we realize that combinations and dissociations may occur that are unknown, and probably never will be known, in isolated form.

When a magma is confined in the depths of the Earth the potentially volatile (fugitive) constituents are presumably in homogeneous solution with the other constituents of the melt. From general chemical considerations we may be sure that the volatility that they will later exhibit is not a factor in determining the combinations in which they exist while dissolved in the magma. The combinations that elements form among themselves on escaping are chiefly conditioned by the fact that these specific compounds are able to escape, but in the magma they simply form parts of the mutually reactive ingredients of a homogeneous solution. Chemical affinity and concentration are the primary factors in bringing about a statistical equilibrium, but thermal impacts effect innumerable temporary changes.

There is no reason to assume that in the melt the hydrogen and chlorine, for instance, that are later given off as HCl , are chiefly in this combination, and a similar inference holds with respect to the hydrogen and oxygen or the hydroxyl and

oxygen that are evolved later as H_2O . Moreover, the degree of dissociation in a melt composed of many reactive ingredients has little relation to experimentally determined values of dissociation for HCl or H_2O when either of these is heated by itself. In the same manner, the non-volatile ingredients may be dissociated or may be combined in a way that is not expressed in the crystalline minerals that are finally deposited.

These principles have been well stated by Zies as follows:

"Indeed it seems futile to attempt to trace any volatile constituent contained in the exhalations of an igneous body to some definite compound unless such a compound has already crystallized from the magma. So long as the magma is fluid all we can safely say is that the volatile constituents are dissolved in the fluid and that they will escape if the fluid magma is supersaturated with respect to the new temperature and pressure environment." (1929, p. 43.)

In non-technical language it may be said that hydrogen and chlorine, as an example, have a strong affinity for each other; and, if HCl became broken up by the impacts to which it is subjected in the melt, the hydrogen and chlorine would by preference unite with each other again, but their concentration in a magmatic solution is so small that as a matter of probability they would collide many times with other chemical particles before they would meet the most appropriate partner. Unions of a second or third degree of affinity would be formed. The conception of kinetic equilibrium requires that there should be a certain amount of HCl present, a certain amount of unattached hydrogen and chlorine, and certain amounts of these in other combination. Each of these has definite numerical relations to all the others.

The same picture of conditions in the magma holds for the elements of water and the other volatiles. A hint of the sort of combinations that volatiles form with non-volatiles is given by such minerals as the micas and hornblendes, in which hydroxyl, fluorine, and chlorine occur. Likewise, the amount of water present seems to have an effect on the relative proportions of ferrous and ferric iron. Such minerals crystallizing out represent only a small fraction that has managed to survive of similar combinations that were present in the melt.

We are now prepared to consider what happens when fugitive constituents are given opportunity to escape. As a simple example HCl will again be taken.

It was indicated that among the various combinations that H and Cl could take, equilibrium required that a certain amount of HCl should be present. This would be the principal volatile form in which chlorine could escape, through FeCl₃, NaCl, and various others in minor amounts can play a similar role.

On relief of pressure the HCl present as such begins to come out of solution in the hot magma and depart as bubbles of gas. This removes from the system one of the constituents on which the whole statistical equilibrium in the solution depended. Reactions are at once set in motion by which an attempt is made to replace the HCl, but, as soon as it is newly formed, it is free to escape. The same idea is applicable to all the other constituents that are capable of forming volatile compounds. It is easy to see that the equilibrium of the whole system is destroyed and the utmost chemical confusion results. In such a state of affairs evanescent combinations are formed which are not in equilibrium with anything.

Suggestions of similar import have been made by other geologists, but usually in a form that emphasizes reactions among unstable associations of gases that might react with each other *after* they leave the magma. These reactions may be very important, but I would emphasize the reactions within the magma itself that lead to the evolution of gases.

In these events each individual reaction between the infinitesimal units is accompanied by a minute heat effect, positive or negative, but the system as a whole is so immensely complicated, and there is so little information in the reactions of separate constituents that no calculation of the net heat effect is possible. The evolution of heat might be very great. If, for instance, combination of hydrogen and oxygen or of hydrogen and hydroxyl to form water were a chief reaction, this would be highly exothermic. Or, on the other hand, the net effect in the system as a whole might be negative. Consideration of certain features not yet discussed will help in deciding which it will be. The value of having such a picture in mind is that it is a guide in directing us to what should be looked for.

At this point it is necessary to recognize that even the general picture given so far has not been made general enough, and that by use of similar conceptions of the conditions within a magma, a somewhat different process might be formulated.

Let us suppose that a silicate mixture plus water is heated in an impervious container until a homogeneous melt is produced. A certain equilibrium is established. Now let us cool the melt until crystals form. The water in the melt thereby becomes concentrated, bubbles are developed, and the vapor pressure over the melt is increased. With further cooling and increasing crystallization the vapor pressure may become very great. A *retrograde* boiling is thus effected by *cooling*. If cooling and consequent crystallization are fairly rapid, the melt may froth up into a pumice.

The significant difference between the first process pictured and the second is that in the first the relief of pressure allowed the volatiles to escape and thereby upset the equilibrium, with possible evolution of heat. In the second process, crystallization upon *cooling* is the important factor. The second process, in its nature, excludes the possibility of the melt becoming hotter; the first recognizes that internal reactions may be exothermic, thereby giving to a magma the power to assimilate xenoliths.

The second process is that which Morey has favored to explain important magmatic phenomena, such as increasing vapor pressure and consequent explosions, formation of pumice, and migration of volatiles into wall rocks. He takes as an illustration the experimental system $\text{H}_2\text{O}-\text{K}_2\text{SiO}_3-\text{SiO}_2$, and shows the rapid increase of vapor pressure that results from the crystallization of quartz and the compound KHSi_2O_6 , and applies the results to magmas as follows (Morey, 1922, p. 226):

"As a magma containing water and other volatile components cools, with consequent crystallization, the pressure will rapidly rise from its initial value, and, as the cooling continues, the pressure will increase until the temperature of maximum pressure has been reached; or until the pressure is relieved by the escape of the volatile material."

He believes that this system can fairly be taken as analogous to natural magmas. Morey explains pumiceous explosions in volcanoes in this manner, and many geologists have accepted his explanation as the chief cause of such effects.

The applicability of Morey's results in this manner seems to require more evidence. Each system has its own characteristics, and the course and speed of reactions in this alkalic system may be quite different from those in natural magmas. The chief reason for dissent, however, will appear in later

sections of this article, where a step-by-step analysis of what occurred in the Katmai eruption will be given. Morey's process calls for cooling and confinement of the magma while pressure is built up. I hope to show that in the Katmai eruption the explosions occurred after the magma rose to the surface and was lying in an open crater, and that during this period a great amount of heat was evolved and large quantities of cold rock from the crater walls were engulfed by the magma and reacted with it. The later explosions developed in the syntectic magma so produced.

We may quote here as relevant a statement by Nernst (1904, p. 675). Under the heading "Temperature and the reaction velocity," Nernst sets forth a general principle: "Let us . . . consider the case where the reaction progresses in the sense which is associated with the *development of heat* (Nernst's italics). As a result of the progress of the reaction, there ensues an elevation of temperature, which in turn accelerates the velocity. But this accelerated velocity . . . occasions an increased development of heat, which again reacts to hasten the decomposition. Thus it is evident how a very extraordinary acceleration of the reaction velocity may take place under favorable circumstances. In this way we can explain the "stormy reactions." *It will be found invariably that these are associated with a development of heat*" (my italics).

This principle is the basis of the following discussion by von Wolff (1919, p. 119), applied directly to volcanism:

"Lowering of temperature, and, still more, removal of pressure are closely connecting with the uprising and extrusion of the magma.

"We shall have to distinguish between two cases:

"1. The change of temperature and pressure proceeds very gradually. In that case the chemical systems have time to adjust themselves to the changed exterior conditions through the bringing about of new equilibria. The condition of equilibrium is maintained. Eruptions that proceed in a non-violent manner, like that of Kilauea, may approach such conditions.

"2. The change of temperature and the unloading occur so quickly that time is not sufficient for the attainment of new equilibria. The chemical systems thereby attain an unstable condition . . . Reactions set in with the goal of reaching the new equilibrium. In this case the velocity of reaction attains a

great significance. *Reactions which . . . proceed exothermally . . . experience through the heat thereby generated a continually increasing acceleration of reaction, which finally leads to explosion.* Through the same processes the gases dissolved in the magma are set free The setting-free of gas is an accompanying phenomenon of the uprise of magma, not its cause" (my italics).

The conception of exothermic "stormy reactions" set forth here by two eminent authorities is a fundamental principle of utmost importance, which should have been of common knowledge for 50 years. Why have geologists in general not recognized it and applied it? Instead they have repeated many times Harker's obfuscating argument against assimilation and hybridization: "The insuperable objection to any such theory is that it demands an enormous amount of heat to raise the solid rocks to the point of melting and to melt them, and no source for this heat is indicated" (1909, p. 339).

Detailed evidence will be presented that a large amount of assimilation did take place in the Katmai magma and that the supply of heat that Harker declared to be non-existent is to be found in the reactions discussed in earlier pages.

In dissenting from Morey's conclusions I would not argue against the principle that crystallization does increase the vapor pressure of the fugitive constituents in a confined system, or deny that in some circumstances it is very important in magmas. Increase of vapor pressure in a confined solution containing volatiles, on cooling and crystallization, is inevitable. One consequence is that it is impossible to ascertain the original volatile content of magmas by studying cold rocks. What I wish to express is serious doubt that Morey's process is competent to explain the phenomena of the Katmai eruption and similar explosive outbursts. Every feature of the Katmai eruption is opposed to it.

THE STRUCTURE OF MOUNT KATMAI

A geologist coming into the Katmai country in the years following the eruption found himself faced with phenomena for which no text-book descriptions, or even experience in volcanic regions that had been less recently and less violently active, would have prepared him. He would be surrounded by factual evidence of volcanic processes for which text-books either gave no explanation or gave explanations obviously out of accord with what he saw.

Explosive eruptions of the magnitude of that of Mount Katmai are exceedingly rare, and the few that have occurred in recent times have been in regions not easily accessible. The products of pumiceous eruptions are easily removed by streams or winds. Ordinarily the ejects have been deposited on contiguous mountainous areas, where erosion is especially rapid, and within a short period some of the most significant evidence of their original relations are likely to have been destroyed or obscured. It was our good fortune to be able to study this uniquely significant region while the evidence was still clear and undisturbed. For this our thanks are due to the Geophysical Laboratory, of the Carnegie Institution of Washington and the National Geographic Society. My second visit to the region was greatly facilitated by the U. S. Geological Survey.

Major problems to which the members of the Geophysical Laboratory staff—Allen, Zies, and Fenner—gave their attention were the following: What was the nature and origin of the great tuff deposit in the Valley of Ten Thousand Smokes? The only previously described deposits that resembled it were those of the West Indian *nuées ardentes* of 1902, and in some respects these were so different that the fundamental similarities were not immediately apparent. What was the composition of the fumarolic gases evolved and the minerals deposited by the fumaroles? What was the explanation of the strangely variegated assortment of pumices erupted? Specimens of white, black, gray, red, brown, and banded pumices in thousands or tens of thousands were visible everywhere. They impressed everyone coming into the region, until by familiarity with their enormous numbers they became commonplace. They were obviously a mixture of felsitic and mafic constituents and for a geologist they were a problem that demanded attention and explanation. How did a mixture of these ingredients in closest association originate? In the main crater of Katmai and the parasitic crater of Novarupta highly explosive magmas had lain quiescent at times and then had detonated with stupendous violence. What internal reactions was the magma undergoing in the quiescent periods? What became of the material that disappeared from the former peaks of Mount Katmai, leaving a great crater pit? Contributions toward the solution of these problems have been published in various articles (Griggs, 1922; Allen and Zies, 1923; Zies, 1929; Fenner, 1920, 1923, 1925, 1926, 1930, 1933, 1934, 1937, 1938, 1944, 1948). In the

present article a large amount of hitherto unpublished data and conclusions as to their bearing will be presented. In order to work these into a coherent picture, it will be necessary to repeat small parts of previous description.

A chart (No. 8555) of the U. S. Coast and Geodetic Survey shows that prior to the eruption Mount Katmai was composed of three peaks, of which the most southerly was 7500 feet (2287 meters) high and the others were 7360 feet and 7260 feet respectively. When the eruption was over only a hollow stump of the mountain was left. (For illustrations see Griggs, 1922, pp. 101, 173, 177, 179; Fenner, 1926, p. 687; 1930, plates II-IX.) The peaks had vanished, and an enormous pit had been formed. Surveys made by the National Geographic Society Expedition show that this abyss is 2.6 miles (4.2 km.) in greatest length and 4.2 square miles in area at the rim. The highest point on the rim (northerly side) has an elevation of 7000 feet (2135 meters) and stands 3700 feet (1128 meters) above the floor of the crater (Griggs, 1922, p. 177). Sags in the rim on the south-eastern and northwestern sides have elevations of about 5100 feet (1555 meters). These are remnants of troughs of glaciers that came down from the upper slopes and were beheaded by the eruption.

In the first years after the discovery the floor of the pit was covered by a lake, from which rose a horseshoe-shaped island. This was the condition in which I saw it in 1919 from the south-eastern rim, but in an ascent of the mountain on the north-western side, in 1923, I found that the lake had disappeared except for a lagoon inclosed by the island. A descent from the northwestern rim to the floor, down a narrow trough, was found possible, and I was enabled to examine the crater at close range. In a number of places on the floor there were boiling springs, and a large mud geyser erupted at frequent intervals (Fenner, 1930, plates II-IX). The floor, in general, was nearly flat, and the former lake had evidently been shallow. The horseshoe island was composed of andesite, platy or ropy. It was believed to have been a final non-explosive extension of lava from the main vent. The lagoon enclosed by the crescent appeared deep.

In the view of the crater in 1919 I had noted that great heaps of debris had slumped from the walls on the northern and southern sides. In 1923 these heaps appeared little changed.

They were estimated to be 500 to 800 feet (150 to 259 meters) high. Similar slumping is believed to have occurred during the eruption, and the masses of rock were submerged in the cauldron of fresh lava and were rapidly attacked.

The character of the walls of the crater is important, but their study from the floor was not altogether satisfactory, for they had been washed over by muddy streams from the rim. It was plain, however, that they were not composed altogether of lavas. On the west side especially, sedimentary strata were discernible. Other parts of the crater wall around the circumference suggested sediments rather than lavas. The most definitely igneous rocks were on the eastern side, where dark red and nearly black masses formed the walls. In the glacial trough at the rim, seen in 1919, were boulders of mafic lavas which had been carried down from the former peaks, and the adjacent rocks in place were lavas.

On the crater floor rock fragments were of considerable variety. Effusive lavas, purple, red, and black, probably predominated, but there was much shale, some of it having a "baked" look. A large boulder of sandstone was prominent. The lavas varied from aphanitic to porphyritic.

In the descent into the crater from the northwestern rim most of the slide rock under foot was sedimentary, generally a hard shale.

The rocks on the outer slopes of the mountain confirm and supplement these observations. On the southeastern rim are lavas only, and lavas cover most of the southern and southeastern side of the mountain. They descend in fairly smooth slopes until they break off abruptly at the canyon of Katmai River (fig. 1). At the bottom of Katmai canyon shales and sandstones crop out under andesites and basalts that rise 1400 feet (425 meters), in steep cliffs. The sandstone surface that passes under the lava has been planed off and scored by unmistakable glacial action over a wide surface. All the lava flows have a topographically youthful appearance and the volcanicity of the mountain may be very young. In contrast, the neighboring Mount Trident has been much more dissected.

The western side of Mount Katmai and the continuation of the range northwesterly are of irregular relief, and even from distant views many peaks are evidently composed of horizontal sediments (Fenner, 1930, plate II). In the course of our ascent

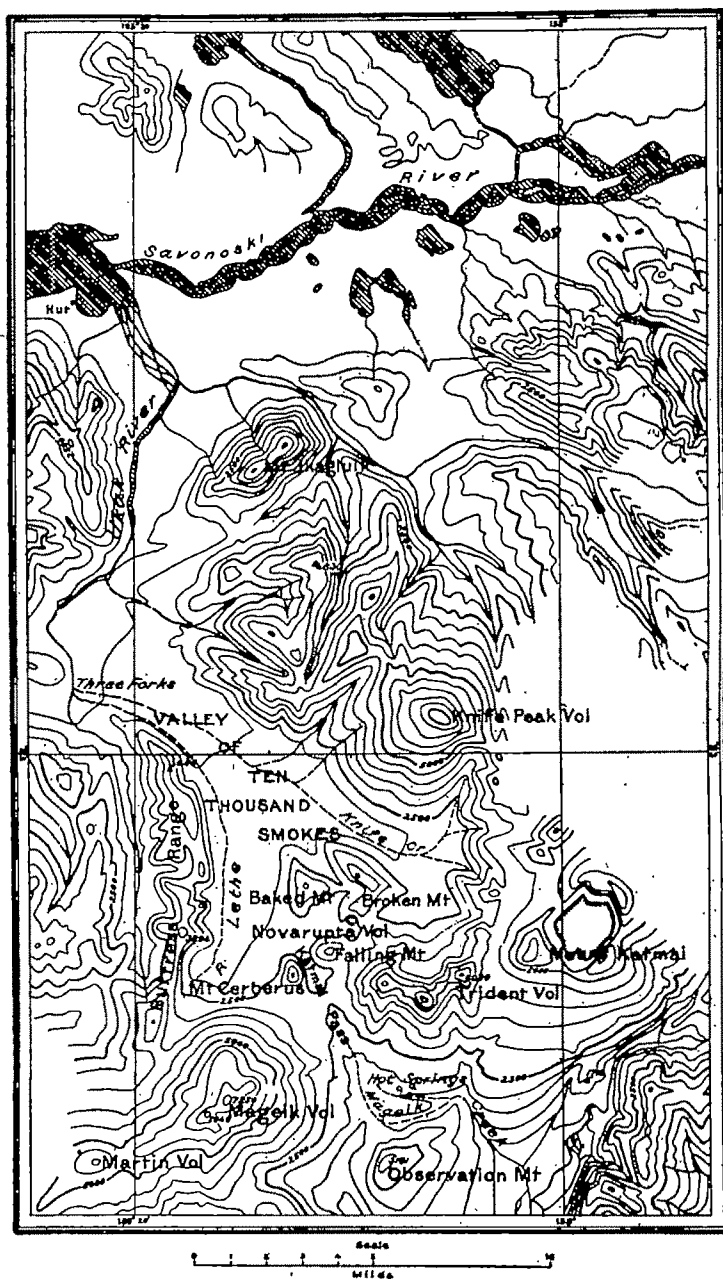


Fig. 1. Map of the Katmai region, from surveys of the National Geographic Society and United States Geological Survey.

on the northwestern side sedimentary rocks were seen to form all the adjacent exposures until we were up near the rim of the crater, where very dark igneous rocks rose in masses.

The sediments in the Katmai region include beds of limestone, and the shales are fossiliferous.

The conclusion regarding the inner walls of the crater pit is that both lavas and sedimentary rocks are present, perhaps in nearly equal amount. The high peak on the northern side is apparently sedimentary, but in most places the sedimentary rocks rose no higher than the present northwestern rim, and on the southeastern side were lacking. The high peak in which the original crater lay was presumably igneous. We shall look for evidence of these wall rocks in the contaminated ejectamenta.

In the Katmai region the most abundant lavas by far that have been poured out by the five volcanoes Katmai, Mageik, Trident, Knife Peak, and Martin are medium to basic andesites and basalts. Many are porphyritic, often with a fine-grained or aphanitic groundmass. The phenocrysts are plagioclase, augite, hypersthene, and magnetite, generally in glomeroporphyritic groups. We should expect to find evidence of these characteristics in the contaminated lavas. Specimens of granitoid rocks are practically absent among the eruptive products. I found not more than half a dozen small specimens in the region. The shattering explosions of the eruption did not reach to great depth. The new magma, as it rose from the depths, was a very siliceous rhyolite, but, as will be shown, it became greatly contaminated by the assimilation of these basic wall rocks.

FEATURES OF THE ERUPTION

The state of the volatiles in a magma, according to the conception given in the preceding pages, must have important consequences on the mechanism of eruption. When relief of pressure gives opportunity for volatiles to escape, they may not be able to take advantage of it immediately. Relief of pressure favors the escape of gases, and therefore reactions proceed in the direction that leads to the formation of gases, but the rearrangements may require time for their development. In a chain of chemical reactions a bottle-neck may occur which slows down the whole series (according to Guldberg and Waag 's conception of variable reaction velocities); but, as we have seen in the quoted statement by Nernst, the speed of

reactions increases rapidly with rise of temperature, and, if the net effect in a magma is exothermic, reactions that have begun very slowly proceed more and more rapidly, at a high compound interest rate, as the temperature rises, and finally reach a cataclysmic stage.

This conception is believed to explain important features of the Katmai eruption. As will be shown, potentially explosive magma that had risen to the surface in the crater remained at times relatively quiescent while it assimilated large quantities of wall rock that had been broken off in masses by the explosions. Possibly corrosive attack upon the walls had weakened or undermined them; at least there was rapid disintegration and assimilation of the submerged blocks. Then the contaminated magma became inflated with great violence because of the sudden setting-free of gases throughout its mass.

In volcanological descriptions we often find statements or implications to the effect that magmas heavily charged with fugitive constituents explode immediately when physical constraints are removed, but, if we read the accounts carefully, we see that in many eruptions that does not agree with the records themselves. The phenomena at Katmai show factors other than physical restraint are extremely important.

The relative duration of the quiescent and explosive periods at Katmai is somewhat uncertain because of lack of direct observations. The nearest of the few native inhabitants of the region were at Katmai Bay and at Naknek Lake, and, wisely, they left before the more violent manifestations developed. Information that bears on the matter is contained in reports gathered by Griggs at distant points (Griggs, 1922, pp. 7-31). A bare digest of the most important is as follows: June 6, 1912, morning; Frequent minor explosions and earthquakes noted at Seldovia (144 miles N.E.) and Nushagak (131 miles W.N.W.). These were probably due to (or accompanied) the outburst of the incandescent tuff-flow in the Valley of Ten Thousand Smokes. June 6, 13 hr.: Terrific explosion and earthquake noted at Cold Bay (40 miles S.W.); smoke cloud seen by captain of steamer "Dora" entering Kupreanof Straits (to the S.E.) and bearings showed that it came from Mount Katmai. "The smoke rose and spread in the sky, following the vessel, and by 3 P.M. was directly over us, having traveled at the rate of 20 miles an hour." This was probably the beginning of the

violent phase of the eruption in Katmai crater, continuing sporadically until June 8. June 6, 15 hr.: Second tremendous explosion heard for hundreds of miles around. June 6, 23 hr.: Severe earthquake at Cold Bay (40 miles S.W.), and a strong glare of light seen from Kanatak (59 miles S.W.). June 6: During the night, a number of severe earthquakes at Kodiak (100 miles E.S.E.). June 7: Earthquakes all day at Kanatak (59 miles S. W.). June 7, 23 hr.: Strong earthquake, with heavy rumbling, rock slides, and glare of light at Kanatak (59 miles S.W.). After midnight, a noise like heavy thunder from the direction of Katmai. June 8-9: Various effects indicate eruption continuing with lessened violence. For the remainder of June and all of July, reports of ashfall and earthquakes from various points.

These reports indicate that the violent explosions took place on June 6 to 8. The periods of comparative rest seem to have lasted longer than the violent phases; in fact, the explosions appear to have been of short duration. The studies of ashfall (see later) confirm the alternations of major explosions with quiet intervals. It is believed that in the quiet periods the assimilation of large quantities of wall rock by the new magma occurred. The submergence of masses of cold rock in the magma probably lengthened the periods of quiet, but it was not the whole cause of the delay, for uncontaminated (or nearly uncontaminated) magma underwent at times a similar pause and subsequent inflation.

The contrast between the dark mafic rock of the walls and the white rhyolite preserved a record of processes at work, which helps greatly in the interpretation of the nature and sequence of events. If the assimilated rock had been of felsitic or even of intermediate composition, it is doubtful if satisfactory evidence of assimilation could have been established, and it might have been completely overlooked.

There are corroborative evidences of open pools of explosive magma standing for a while in the crater before bursting forth. The most common product of the eruption was highly inflated pumice, but a material that I have called "volcanic scum" was found everywhere within the area of coarse ejecta. It occurred as angular blocks, rather flat, three or four inches (7.5 to 10 cm.) thick. These blocks are interpreted as fragments of a crust that congealed at times at the edges of the pool. Many

specimens were collected, and supplied interesting information. In a matrix of glass which was intrinsically dark but so filled with tiny bubbles that it appeared gray, was a heterogeneous collection of xenoliths and xenocrysts—angular pieces of old lavas, sediments, obsidian, pieces of scum from previous explosions, pumices and separate crystals—collectively representing the sort of scum that might be expected on the surface of the miscellaneous stew that the magma had become. The fragments of pumice included in this scum appear to have been somewhat softened by re-immersion and have lost their highly inflated character but are still very vesicular and are easily identified. Some have retained their angular form, but others have been drawn out into bands.

We should naturally expect that pumice which had been ejected and had fallen back would float on the surface of the lava, but accompanying it in the blocks of scum is rock of much greater density. This must have been carried to the surface by rising currents in a seething pool, and the whole conglomeration swept to one side, into a cooler situation where it congealed.

Examination with a binocular magnifier shows that narrow tongues or irregular apophyses of glass penetrate the xenolithic inclusions of the blocks. Thin sections of the "scum," studied microscopically, reveal clearly what was happening to xenoliths. Feldspar phenocrysts are riddled with brown glass, especially in certain of the oscillatory zones, and pyroxenes are attacked and penetrated by glass.

If phenocrysts weakened in this manner had not been held in a rigid glass during subsequent explosions, they would generally have been torn apart, and the distinct evidence of attack would have been destroyed. Occasionally specimens from the stratified ashfall show an intermediate stage. Parts of phenocrysts that were originally single units, but are now slightly separated, have their fractured surfaces attached to each other by threads of glass.

A substance related to the "scum" is a very dark (nearly black) glass with or without inclusions. This also probably formed a crust at the edges of the lava pool. When heated over a Bunsen burner it froths up into pumice. Evidently it retained some of its volatiles during congelation.

The high mobility of the magma is shown by its ability to

penetrate xenoliths. Among the ejecta of Mount Katmai and Novarupta are many specimens of scoria and pumice so dark-colored and basic that they are believed to represent blocks of basic lavas which were submerged in the liquid magma and became softened clots, but had not yet mingled freely with the liquid. Nevertheless many are much inflated. It is thought that the rhyolite liquid was so highly mobile that it soaked into these xenoliths and permeated and softened them so thoroughly that they became inflated at the same time as the liquid magma. Specimens of this sort are more common in the ejecta of Novarupta than of Katmai. Though they are fairly common in the ejecta of Katmai, on the whole, assimilation in the crater of Katmai progressed further and more nearly homogeneous products resulted.

The view that rhyolitic magmas are essentially highly viscous seems to persist in spite of much evidence to the contrary. When they have lost their volatiles and have been somewhat cooled, they are viscous as warm tar, but, in their pristine condition, they flow freely and soak into xenoliths without difficulty. Among the great rhyolite flows in Yellowstone Park all degrees of viscosity may be observed.

THE STRATIFIED KATMAI ASHFALL¹

During the eruption of Mount Katmai a large quantity of ash was carried by the wind to the town of Kodiak, 100 miles (161 km.) distant to the east-southeast. In 1919 a measured section was found to be 10 in. (25 cm.) thick, after seven years of settling and packing. The wind direction during the eruption was toward Kodiak, but five hours was required from the beginning of the first violent phase of the eruption, as observed by the captain of the steamer "Dora" in Kupreanof Strait, to carry the ash 100 miles. Therefore the wind was not violent. That the ash took so long to settle means that it was thrown to a great height. This ash was not an impalpable dust. The bottom layer consisted of 4½ in. (11½ cm.) of light-gray

¹The term "ashfall" will be used for the accumulations of ejecta from Katmai and Novarupta that had been thrown violently into the air and had settled over the surrounding country. Most of it was pumice, but it contained small amounts of some un-ashlike materials. It is to be distinguished from the incandescent tuff-flow (abbreviated in places here to "incandescent tuff") that was ejected with less violence and flowed over the surface of the ground.

sand; the second measured 4 in., light-brown sand at bottom, very fine sand at top; and the top layer was $1\frac{1}{2}$ in. of light-gray, fine sand. Most of the material was glass of index 1.480, but it contained calcic feldspars and rare fragments of pyroxene. The five-hours of travel had made only a partial winnowing of heavy material from light.

In the opposite direction from Mount Katmai, that is, to the northwest, and about 21 miles (34 km.) from Katmai, a section of ashfall at one camp on Naknek Lake (northwest corner of map) measured $10\frac{1}{2}$ in. (26.6 cm.) in depth. There was not much differentiation of layers by size of particles except for one coarse layer. The same minerals were present as at Kodiak.

Much thicker layers of undisturbed Katmai ejecta are present near the mountain, on the south and southwest, in the valley of Katmai River. Recent stream-cutting had exposed sections well situated for close examination and sampling. Study of these on the ground and petrographic and chemical investigation in the laboratory gave much important information on what processes were at work in the course of the eruption.

Three sections of Katmai ashfall on the western side of the valley of Katmai River were measured and studied in 1919 and two others in 1923. The first was at our Camp IV (near southeast corner of map, a little north of point where Mageik Creek leaves the map). The other two sections of 1919 were at points farther south, and the two of 1923 farther north. The thickness of the deposits lessened quite rapidly in going south from Camp IV and increased in going north. In all the sections, corresponding layers were very similar.

The deposit at Camp IV and one of those studied in 1923 will be described as typical. The description of the layers will follow the order of deposition: A-175 is the bottom layer.

KATMAI ASHFALL AT CAMP IV

The lowermost layer rests on old turf.

A-175. 18 in. (45.7 cm.) of coarse pumice. Largest pieces (omitting exceptional ones) are 3 to 4 in. (8 to 10 cm.) long. The pumice is pure white, but it is mixed with stony lapilli. There is very little difference in size of pumice lumps from bottom to near the top; then a rapid change takes place and

the top 1 in. is of pea size or less as an ordinary maximum, with most pieces much less. There is almost no very fine material to fill interstices. A large part of the lapilli is black and red, stony (not glassy) andesite, but there is also burnt-looking shale. The quantity of lapilli is hardly sufficient to suggest that they represent the blasting-out of an old plug in the conduit, but rather that there had been some accumulation of loose rock. Neither is there in the composition of A-175 any evidence that it had to melt out a plug of old lava before it could rise into the crater. The pumice of this first layer is purest rhyolite (see analyses, table 1). No streaked or variegated (black-and-white) pumice was observed.

A-176. $3\frac{1}{2}$ in. (9 cm.) terra-cotta layer, of hickory-nut size (3-4 cm.) at bottom, decreasing rapidly and progressively to very fine (sandy) material mixed with some coarse at top. The lumps of pumice are generally white, but there are dark pieces and black-and-white streaked pumices, evidence that assimilation of basic rock had begun (see table 3 and diagram of analyses). The terra-cotta color seems to be due entirely to a coating of fine mud.

A-177. 11 in. (28 cm.) buff layer. Coarse pumice, up to maximum of 2-3 in., with very little fines. Contains white, gray, red, striped and nearly black pumices, stony andesites, burnt shale, and dense glasses, both dark and variegated. Assimilation had greatly increased, but products have not been uniformly mixed.

A-178. 2 in. (5 cm.) yellow layer. Essentially the same as last, except that many pieces of pumice are stained a bright orange color—evidently volatile iron compound had been evolved. The lumps in this layer are somewhat smaller than in layer below and A-178 might be considered the top portion of A-177. In A-179 the size increases again.

A-179. 9 in. (23 cm.) buff layer. Made up largely of buff or reddish-brown pumice, coarse. Not so much very dark pumice as in A-177 and A-178. Contains fragments of stony andesite, burnt shale, and dense glasses, both dark and variegated. Pumice has become more uniformly basic. Assimilation and mixing are far advanced. The top of A-179 is less coarse than lower portion; and is succeeded by coarser in A-180.

A-180. 50 in. (127 cm.) gray layer. Major outburst. Very coarse at bottom and for most of its thickness, with lumps up

TABLE I

Analyses of pumices of the eruption. Nos. A-175 to A-187 are successive layers of ashfall. Column of combined analyses gives calculated composition of average pumice.
 A-505 is pumice from a second section corresponding in position of A-181 of first section.
 A-547 is andesite of horseshoe island in Katmai crater.
 A-185X is white pumice selected from basic sample A-185.

	A-175	A-176	A-177	A-178	A-179	A-180	A-181	A-182	A-183	A-185	A-186	A-187	Combined Analyses	A-505	A-547	A-185X
SiO ₂	76.53	75.56	71.92	69.37	64.61	65.96	68.00	67.43	60.35	57.99	63.56	64.36	69.14	67.48	65.90	75.08
Al ₂ O ₃	12.31	12.10	13.30	14.28	15.40	14.93	14.59	14.52*	16.28*	17.39	15.72*	15.31	14.34	14.51	15.89	12.13*
Fe ₂ O ₃	.46	.77	.81	1.44	1.97	1.91	1.66	0.92	2.70	2.76	2.73	2.75	4.41	1.46	1.61	2.25
FeO	.96	1.06	1.97	2.54	3.50	3.11	2.75	2.95	4.68	4.75	3.67	2.50		2.99	2.70	
MgO	.00	.59	1.11	1.66	2.24	2.07	1.65	1.53	3.17	3.42	2.48	1.99	1.68	1.66	1.90	.82
CaO	1.01	1.54	2.88	3.77	5.23	4.95	4.07	4.08	6.06	7.49	5.39	4.29	3.88	4.02	4.55	1.55
Na ₂ O	4.15	4.09	3.99	3.78	3.78	3.37	3.92	3.88	3.84	4.03	4.00	3.62	3.95	3.88	4.11	
K ₂ O	3.05	3.00	2.53	2.18	1.77	1.74	1.98	2.16	1.85	1.06	1.62	1.56	2.12	2.20	1.69	
H ₂ O+	.87	.73	.67	.56	.37	.37	.42	0.67	.46	.38	.54	1.33		.47	.42	
H ₂ O-	.25	.22	.16	.18	.16	.11	.13			.07	.72	.78		.15	.15	
ThO ₂	.17	.19	.33	.47	.65	.59	.53	0.55	.94	.81	.72	.59	0.48	.52	.62	.27
MnO	.04	.05	.07	.09	.09	.09	.07	n.d.	n.d.	.15	n.d.	.10		.09	n.d.	
BaO	.07	.07	.07	.08	.07	.06	.05	n.d.	n.d.	.05	n.d.	n.d.		.06	.05	
P ₂ O ₅	.05	.01	.08	.16	.19	.13	.14	n.d.	n.d.	.22	n.d.	.16		.26	.17	
Cl	.28	.20	.17	.14	.15	.13	.13	n.d.	n.d.	.07	n.d.	.09		.14	n.d.	
S	.01	.01	.03	.03	.03	.04	.02	n.d.	n.d.	.07	n.d.	.17		.08	.25	
	100.16	100.19	100.09	100.68	100.21	100.08	100.10	98.35	100.35	100.69	100.43	100.04	100.00	99.97	99.86	

*Incl. P₂O₅

to 2 or 3 in. ($5\frac{1}{4}$ -8 cm.). Top 20 in. (50.5 cm.) considerably finer, with maximum of pea size. In this top 20 in. there is a minor stratification due to alternations of size, grading into each other. In A-180 as a whole there is very little really fine material. Pumice predominates over dark lapilli much more than in lower layers. The general color effect is uniformly gray, but white, light-gray, buff, and terra-cotta varieties are present. There is little or no very dark pumice. Assimilation and mixing have well advanced toward homogeneity. The top of A-180 is separated sharply from A-181.

A-181. 8 in. ($20\frac{1}{2}$ cm.) light-gray layer. In lower 5 in. the pumice is coarse, with many lumps 2 in. (5 cm.) in length. Then it changes quite rapidly to a grit or coarse sand at top. Is composed mostly of white pumice, but there is a little gray and terra-cotta pumice and dark lapilli. The large amount of white pumice shows that there had been an important new upsurge of rhyolite magma, and that this had not mixed thoroughly with the contaminated lava when inflation occurred. Very likely there was a fairly continuous upwelling of fresh rhyolite into the crater all through the eruption, for none of the principal layers of the ashfall is homogeneous—all contain some white pumice—but in A-181 the amount becomes large. A-181 is separated sharply at top from A-182.

A-182 8 mm. fine sand, light-gray.

A-183 10 mm. light-gray grit or coarse sand.

A-184 6 mm. fine sand, light-gray.

A-185 36 mm. light-gray grit.

A-186 28 mm. light-gray sand.

A-187 35 mm. dark reddish-brown sand below, purple sand above.

Layers A-182 to A-187 are sharply separated from each other.

A thin deposit of purple or lavender sand or mud (A-187) is generally present on top of the ashfall over a wide area.

Noteworthy is the evidence of repeated dying-down and renewal of explosive activity, shown by the decreasing size of the ejecta toward the top of each important layer, the sharp break between layers, and the increased size of pumice deposited at the succeeding outburst. Inflation and ejection of the magma, when once begun, was not a process that continued until all the potentially explosive magma on hand was exhausted; in-

stead, the inflation reached to a certain depth of magma in the crater and then halted for a while until internal reactions had set free the latent explosivity of another portion. The portion of magma that exploded at any one outburst was that from which volatiles had been free to escape into the atmosphere, thus setting off the chain of internal reactions that developed the latent explosivity and culminated in the outburst.

Further description of the pumices and their minerals will be given in the petrographic section.

Perret, who contributed greatly to volcanological knowledge by years of study, at close range, of eruptions in actual progress, has described similar delayed explosions witnessed during the eruption of Mount Pelée in 1929-1932:

"Certain conditions displayed in the present eruption had been hitherto unknown at Pelée; among them the presence of liquid lava in pockets and vents, open to the atmosphere, where the well-known crater glow persisted for days at a time. From these craters occasionally burst forth nuées ardentes." (Perret, 1935, p. 86). He considered it somewhat remarkable that at Katmai it had been possible to deduce this phenomenon without its having been witnessed. Actually, the evidence at Katmai was so clear that it could hardly be missed.

SECOND SECTION ASHFALL IN KATMAI VALLEY

The next section of ashfall to be described was at a point four or five miles north of the first section and about four miles due south of Katmai crater. Plate 1 is a photograph of this deposit. This section was studied with special care in 1928, as a check and confirmation of the studies of 1919, after the material collected then had been worked over petrographically and chemically in the laboratory.

This second section was as follows:

At bottom, boulders, overlain by a fibrous mat of dead turf, roots and twigs.

A. 48 in. (122 cm.) Pure white pumice, mixed with lapilli of basic to medium lavas and sediments. The igneous rocks are reddish-brown, purple, gray, and black, and are generally porphyritic. They have the appearance of the lavas seen in place in various localities around Katmai. (Note later, in the petrographic section, how the character of these lapilli agrees with the character of fragments in the succeeding layers of

pumice that have been attacked and are in process of solution.) The sedimentary lapilli are both shale and sandstone, the former preponderant. Many are blackened, some reddened. The lapilli occur throughout layer A. Are more plentiful in bottom 18 in. (46 cm.), but are mixed with pumices there as throughout the layer. Are mostly in small bits but occasionally reach 2 in. in diameter. Are of angular shapes. Sedimentary rocks exceed igneous lapilli. An estimate of foreign lapilli in lowest 18 in. of A was 15 to 20 per cent by volume. This amount of *unassimilated* xenoliths is much greater than in succeeding layers. The pumices are all in angular pieces, with no rounding even of edges. Most of them are firm but an occasional piece is very frothy. Ordinary maximum size is 2 to 3 in. (5 to 8 cm.), but pieces of 5 in. occur. All the pumice is pure white, except that two light-gray or faintly banded pieces that contained a few dark phenocrysts were found after close scrutiny of many lumps. A small amount of pumice is superficially stained yellow. No phenocrysts of quartz or feldspar are visible (i.e., in the examination in the field). The interstices among lumps are filled loosely with fines. In top 1½ to 2 in. of this layer few pieces are larger than pea size.

B. 1½ in. (4 cm.) buff layer. The lumps of pumice are still perfectly white and without phenocrysts, but buff-colored mud coats the pumices and partly fills the interstices. The lumps are ½ in. in diameter as an ordinary maximum. Shale and andesite are present. B is very much like A except for the buff mud, but this makes the layer distinct.

C. 16 in. (41 cm.) light-gray or buff. Most of the pumice is white, with very sparse dark phenocrysts (xenocrysts), but there is a considerable amount of brown and gray pumice with phenocrysts, also variegated (striped) pieces. Sedimentary fragments and igneous lapilli are less than before. Lumps of pumice are angular. In most of C the ordinary maximum is 1½ in. (4 cm.), but in upper 1½ in. there are more fines. A minor horizontal banding of layer is visible. The notable feature of C is the sudden appearance of a considerable quantity of dark and variegated pumices with xenocrysts. The striping of the pumices is distinct and unmistakable. (Assimilation has advanced, but homogeneity has not been attained.)

D. 5 in. (13 cm.) yellow or orange layer. White pumice without phenocrysts is still present, but most is brown, gray,

pink, or yellow, with dark phenocrysts. The first appearance of volcanic conglomerate ("scum") is noted in D, and the pieces are numerous. The yellow color that distinguishes D is probably a stain but is very pronounced. Distinct fragments of sedimentary rocks and mafic lavas are still present, but the quantity is becoming small. Striped pumices are not so common in D as are those that are brown or gray throughout. These contain large quantities of dark xenocrysts. Ordinary maximum of size of pumice is $1\frac{1}{2}$ in. A minor layering, with variations of size, is visible in D.

E. 8 to 9 in. ($21\frac{1}{2}$ cm.) light-brown stratum.

F. $2\frac{1}{2}$ in. ($6\frac{1}{2}$ cm.) yellow.

G. 4 in. ($10\frac{1}{2}$ cm.) yellow.

H. $2\frac{1}{2}$ in. ($6\frac{1}{2}$ cm.) yellow.

The characteristics of these four layers are not very different from those of D. The yellow color that distinguishes F and H sharply is probably a stain, and the real color of the pumice is brown or gray. Very little white pumice in these four layers. Most pieces carry plentiful xenocrysts (set free from the lavas). Striped pumices are not nearly as numerous as those that are brown, gray, or brownish-pink throughout, though they occur. Fragments of sedimentary rocks and basic lavas are still present. In addition to variations of color there are several alternations in proportions of coarse and fine, apparently not strictly following changes of color. Ordinary maximum size is $1\frac{1}{2}$ in., but pieces of 2 or 3 in. occur. Fines of wheat size fill interstices loosely as in layers below. Volcanic "scum" is not plentiful; black glass is rare or lacking.

In none of the layers A to R was black glass observed as a plentiful constituent; nevertheless, in traveling about the region much of this glass was seen, perhaps concentrated by the removal of light pumice by the strong winds. My impression was that layer D was its principal home; perhaps layers E to H also.

I. 48 in. (121 cm.) coarse gray layer. Many lumps of pumice are 2 to 8 in. in diameter, with a maximum of 4 in. (10 cm.). The average is coarser than in layers E to H. Pumice of wheat size fills interstices, but the whole of I is very loose. Dark or variegated pumices are rare. The color of the whole

· Plate 1. Katmai stratified ashfall (lower half of section) overlain by Katmai incandescent tuff-flow.



is a uniform gray. There is an indistinct stratification throughout, due to variations of coarseness. In the upper one-half there is a progressive decrease of coarseness, but the separation from the next layer is not sharp. Probably I, K (and ?L) should not be regarded as separate outbursts, but as one outburst that varied in intensity.

K. 18 in. (46 cm.) fine gray layer. Characteristics are nearly those of I but size of pumice is less. A few pieces are 1 in. in diameter, but most of it is about wheat size. Loose crystals of pyroxene are abundant.

L. 21 in. (53 cm.) coarse gray layer. Like I and K, but there is a sudden increase of coarseness. Pieces 1 to 2 in. are common. Pumices are light-gray and contain dark xenocrysts. L becomes finer toward the top, but the change to much finer in M is sudden.

M. $\frac{1}{2}$ in. (1.5 cm.) of fine flour; gray, stained yellow.

N. 2 in. (5 cm.) coarse sand; gray, stained yellow.

O. $\frac{1}{2}$ in. fine flour; gray, stained yellow.

P. 5 in. (13 cm.) at bottom it is a grit. Contains small pumices up to pea size. At top it is a coarse sand. Color is gray, stained yellow.

Q. 3 in. (8 cm.) fine sand, not sharply separated from P.

R. $1\frac{1}{2}$ in. lavender-gray mud.

On top of these layers of ashfall is the incandescent tuff-flow from Mount Katmai (plate 1). This incandescent tuff is the final phase of the eruption from Katmai, whereas in the Valley of Ten Thousand Smokes the incandescent tuff preceded the explosive eruptions from the parasitic cone of Novarupta.

In table 2 correlations are made between the two described sections of ashfall. The strata preserve their identifying characteristics from one to the other, but thickness varies somewhat. In places where a long section of ashfall is exposed minor partings are visible in the thicker strata. Some of these were indicated in the descriptions. They may have been caused either by small differences of eruptive intensity or possibly by shifting winds during the downfall.

PETROGRAPHY

The pumice samples collected from the sections of ashfall contained fragments of igneous rocks (mostly basic andesites and basalts), of sandstone and shale, of glomeroporphyritic

groups of orthopyroxene and clinopyroxene, calcic feldspars, and iron ore, and also individual crystals of these minerals dissolved out of this matrix, fragments of obsidian (black glass), and "volcanic scum" (agglomeratic crests on lava pools). With these were small loose crystals of quartz and sodic feldspar, brought in by continual influx of new magma, and

TABLE 2

Correlation of sections on northwest side of Katmai Valley.

<i>Section No. 1</i>	<i>Section No. 2</i>
A-175 18 in.; pure white layer; coarse, but fine at top; many lapilli.	A. 48 in.; pure white; coarse, fine at top, many lapilli.
A-176 3½ in.; terra-cotta layer; coarse at bottom to fine at top; mostly white pumice coated buff.	B. 1½ in.; white pumice coated buff; coarse.
A-177 11 in.; coarse; buff, together with white, gray, red, striped, and nearly black pumice.	C. 16 in.; light-gray or buff as a whole, but contains white, brown, gray, and striped; coarse, but finer at top.
A-178 2 in.; very like A-177 but many pieces stained bright yellow; medium fine.	D. 5 in.; yellow or orange but color is a stain; brown, gray and white pumice.
A-179 9 in.; buff; coarse, finer at top.	E. 8 to 9 in.; light-brown. F. 2½ in.; yellow. G. 4 in.; brown. H. 2½ in.; yellow. These four are not very different from D; color a stain.
A-180 50 in.; gray, but some white and terra-cotta pieces; very coarse but finer at top.	I. 48 in.; very coarse; uniform gray except some variegated. K. 18 in.; fine gray; much like I but size of pumice is less.
A-181 in.; light-gray in general, but white pumice prevails; coarse at bottom, sand at top.	L. 21 in.; coarse gray; similar to I and K but size is greater; fine at top.
A-182 8 mm.; sand.	M. ½ in.; fine.
A-183 10 mm.; grit.	N. 2 in.; coarse.
A-184 6 mm.; fine sand.	O. ½ in.; fine, some lumps.
A-185 30 mm.; grit.	P. 5 in.; coarse, fine at top.
A-186 28 mm.; sand.	Q. 3 in.; fine.
A-187 85 mm.; red-brown to purple sand.	R. 1½ in.; lavender gray.

soon disappearing as assimilation and mixing progressed. Preliminary examination in the field showed that, as the outbursts continued, the outward characteristics of inclusions recorded the effects of immersion in the lava pool. Laboratory studies enabled a somewhat quantitative evaluation of these results to be obtained. A weighed portion of each sample of the section at Camp IV was separated into various parts by sifting. Fractions passing through sieves of 10, 20, or more meshes to the inch were obtained. From these, the darker bits were picked out under a binocular magnifier, and each was placed in its proper category. Most of the quartz phenocrysts were obtained in the finer siftings, and were likewise picked out.

The constituents of the coarse lumps of pumice were not thus separated—this would have been impracticable, and also it was thought that their contents would be in about the same proportions as in the siftings.

By this method, hundreds of bits of material were separated and the weight of each group determined. The results are given in table 3. It is believed that the results express fairly closely the relative amounts of these various constituents of the ashfall and give much information on what was happening in the volcanic crater during the eruption. The inferences are supported by the chemical analyses, given later. It had become

TABLE 3
Percentage of various constituents in strata of
Katmai ashfall at Camp IV.

Stratum	Loose		Sediments	Volcanic		Quartz
	Andesites & Basalts	Igneous Crystals		Obsidian	Scum	
A-175	11.91	.06	2.6	—1.00—		.422
A-176	4.25	.56	10.0	.08	.80	.299
A-177	1.98	1.59	1.48	.64	1.90	.368
A-178	.47	4.7	.30	1.16	.66	.207
A-179	.18	4.87	.11	.116	.33	.079
A-180	.00	5.58	.21	.287	.00	.068
A-181	.03	8.48	.12	.127	.00	.082
A-185	.00	13.30	.00	.07	.00	.043

Note. For all the constituents except quartz, the figures show the percentage of the given constituent in the portion of the sample above 10 mesh (in No. A-185, above 20 mesh). For quartz the figures represent the percentage of quartz in material between 20 and 35 mesh to the whole sample. In other words, the percentage figures for quartz are comparable among themselves but not quite (though nearly) comparable with the others.

apparent in previous sections of this article that the first material erupted was a very siliceous soda rhyolite with little or no contamination by dissolved foreign material but with discrete fragments of rocks from walls. In succeeding outbursts more and more foreign material from the walls became involved and assimilated.

Table 8 shows, in approximately quantitative terms, what happened to xenoliths that became immersed in the new magma. At the first outburst the only extraneous material accompanying the white pumice was in the form of a mechanical mixture. These xenoliths were in discrete, unaltered lapilli, of which the character was easily recognizable. The lavas were andesites and basalts.

Detached igneous crystals were absent in A-175. In later strata they have become very abundant. At the same time the discrete fragments of lava are much decreased in amount. The detached crystals in these later stages are evidently due to the setting-free of phenocrysts by solution of the matrix of the mafic wall rocks. To make certain of this their characteristics in the two environments were carefully compared. Those in the lapilli were studied in thin sections microscopically, and also under a binocular magnifier in the many specimens of lapilli in which corrosion of the aphanitic groundmass had left the phenocrysts in relief.

In the second environment the phenocrysts that had been set free occurred either in lumps of pumice, or as inclusions in obsidian or "scum," or as loose crystals, and were studied by the same methods as were applied to the lapilli. The characteristics in the two environments were identical. The crystals of the mafic minerals, singly or in groups, have certain characteristics of size, form, and association, and these characteristics appeared unmistakably the same in the pumices as in the lapilli of andesite and basalt.

The processes of attack upon the xenoliths involved either an intimate penetration and consequent softening of the whole mass, followed by dispersal of the phenocrysts, or the breaking-up of the fragments by attack along fissures, simultaneously with solution of the groundmass around the periphery. The glass surrounding xenoliths and xenocrysts has become streaked with brown threads. Finally, multitudes of phenocrysts of the kind that the xenoliths carried are found in the later strata

of the ashfall, though the earlier strata are practically free of them.

The phenocrysts of the pumices are thus identified with those of the lavas of the former crater walls.

Bits of sedimentary rocks appeared in considerable force in the first two outbursts, and then nearly disappeared, leaving little trace. The reason for this will appear in connection with the analyses.

Quartz, in small crystals, was present from the first as an accompaniment of the new rhyolite, but even at this early stage many of the quartz phenocrysts were embayed by corrosion. The quantity rapidly decreased, but a small amount continued to appear throughout the series. It is inferred that it was resorbed rapidly, but that the supply was continually replenished by new rhyolite/magma that kept welling up into the crater. This new rhyolite did not become thoroughly mixed up with the contaminated magma at once, but, still unmixed or partially mixed, it was ejected in the explosions and showed up in the ashfalls as separate lumps of white pumice or in the black-and-white striped pieces. It is accompanied by sodic plagioclase. Even in stratum A-185, in which so much mafic rock had been assimilated that the silica content had dropped to less than 58% (on a non-volatile basis), careful treatment with H_2SO_4 , HF , and HNO_3 dissolved everything except quartz and left a considerable number of quartz crystals.

The presence of quartz in the new rhyolite supplies information on the upper limit of temperature, when the lava first rose. The transition point between quartz and tridymite is 870°C . If the quartz phenocrysts had been formed at considerable depth the transition point would have been raised, but probably not higher than 1000°C .; that is, the magma was not greatly superheated. Its ability to dissolve xenoliths cannot be attributed to excess temperature at the beginning but must be laid to the development of heat by exothermic reactions.

The new magma A-175 contained a little primary plagioclase. Its indices showed Ab_6An_4 , oligoclase-albite, appropriate to the rhyolite. The small crystals were rather more numerous than those of quartz. They were likely to crumble when picked out of the pumice, and were often surrounded by a mixture of

crystal fragments and glass. Although there is no quartz in A-175, the quartz and plagioclase crystals show signs of resorption. Exothermic reactions have been observed, indicating instability.

In the hybridized pumices phenocrysts (x) calcic plagioclases were abundant. They show a composition, as was appropriate for the volcanic basalts that are believed to have been erupted, ranging from An_{27} to An_{82} . The manner in which the pyroxene crystals in the "scum" became resorbed has been described on a previous page. Some of the pumices picked out of the pumices showed the same composition of feldspars was considered as an indication of the nature of the basic rocks that had their original home, and many determined. Although the indices varied widely, they were all around a value indicative of a mineral on the scale between labradorite and andesine, or An_{55} (S). From previous studies of many of the rocks in the Katmai region, this feldspar would be appropriate of about the same silica content, or 54 per cent silica toward which everything points are members should be a rock or mixture of rock with 54 per cent silica. Confirmation of this is given in the section on Analyses.

It was such a rock or mixture that was new rhyolite magma to give the service of hybridizing sedimentary rocks that also became involved in the eruption are left out of consideration. It has been shown that the solution of fragments of them in the first two explosions of them was to be seen. The analyses will show that the igneous lapilli of the first explosions likewise were such, but their phenocrysts appear as xenocrysts. At the same time solution of their glass and corrosion of the phenocrysts have resulted in the glasses of the later pumices. The amount of glass mixed with the rhyolite, and therefore the composition, was basic as would be appropriate for the original rocks that the phenocrysts. As a result the phenocrysts were those of andesites or andesitic basalts, but they were in a glass that is not in accord. Its index in

A-180, for instance, is that of a glass of 71 to 72 per cent silica content, with striae of higher index running through it. These striae are like those that appear as defects in the manufacture of optical glass when a melted batch has not been sufficiently stirred to smooth out inhomogeneities caused by attack on the pot walls.

(To be continued)

THE NATURE AND RELATIONSHIPS OF THE PALEOZOIC MICROSAURS

ALFRED SHERWOOD ROMER

ABSTRACT. An attempt is made to establish a series of characters whereby the small Paleozoic tetrapods usually termed microsaur may be defined. A considerable number of Carboniferous and early Permian genera belong to this category, but other genera which have frequently been included do not pertain. Although the "type" microsauro, *Hylonomus*, is among the forms excluded, it seems best to retain the familiar ordinal term *Microsauria* for the group as here defined. The microsaurians appear to have no relationship to reptiles, but are possibly ancestral to the urodele and apodous amphibians.

FOR a number of years I have been engaged in a review of our knowledge of the older, pre-Jurassic fossil Amphibia, attempting to place them in a reasonably consistent phylogenetic and systematic framework—this not as a definitive arrangement, but with the aim of furnishing a point of departure for future work. I have from time to time made "reports of progress" in one form or another (as in Romer, 1940, 1941a) and have incorporated the results of the earlier stages of this work in the revision of my text in vertebrate paleontology (1945a). I have recently reviewed the Labyrinthodontia in rather comprehensive fashion (1947).

There remains for consideration a second major group. This I have called the Subclass Lepospondyli, using this term in a very broad sense to include the existing Urodela and Apoda (Gymnophiona) as well as various ancient fossil forms. In the labyrinthodonts the vertebral centra appear to have ossified from varied cartilaginous "arch" centers; in the lepospondyls the centrum is characteristically a spool-shaped unit structure, formed, it would seem, as a direct ossification in a mesenchyme sheath about the notochord.

A very considerable amount of material has been assigned, from time to time over the past century, to the various Paleozoic groups which I include in the Lepospondyli. Our knowledge of these forms is, however, quite unsatisfactory in almost every instance. Most are animals of small size, with a body length, generally, of but a few inches. This in itself tends to make accurate observation difficult. A majority are preserved in flattened, two-dimensional form, frequently on slabs of

shale or "cannel"; this adds a further handicap. Specimens from the Coal Measures constituting a considerable proportion of the material, are frequently "diseased" through the presence of pyrite, and tend to disintegrate, thus making it impossible to verify or amplify the studies (often superficial) of the original describer. Much of the material is fragmentary in nature—disembodied heads, headless trunks, disarticulated partial skeletons, often with dubious association of various elements. As a consequence our knowledge of the Paleozoic lepospondyls is tantalizingly inadequate, despite the attention paid them in early days by such men as Dawson, Huxley, Cope, Fritsch, and Credner, and even despite valuable revisionary studies of recent years, of which those of Steen are outstanding.

A plethora of names, mainly of ordinal character, has been applied to the various components of this ancient lepospondyl assemblage. A pattern which many have followed, and to which I have very tentatively adhered, was established as a result of the report of the Miall Committee (on which Huxley presumably played an important role). In this report (Miall, 1875, p. 151) most of the amphibians to be considered here were ranged in three groups: Nectridia, Aistopoda, and Microsauria. The Nectridia are, despite skull modifications, a clear-cut group, abundant in the late Pennsylvanian and surviving into the early Permian; the double fan formed by neural and haemal arches of the caudal vertebrae is an unmistakable nectridian trademark. The group Aistopoda was formed to care for two elongate, eel-like or snake-like types found in the Carboniferous, of which *Ophiderpeton* and *Dolichosoma* are representative. There is little or no evidence that the two are related rather than parallel (cf. for example, J. T. Gregory, 1948b), but we will not concern ourselves here with this problem.

DEVELOPMENT OF THE MICROSAUR CONCEPT

In the year 1858 a paper by Lyell and Dawson (with addenda by Owen and Wyman) announced the discovery of the remains of tetrapods in tree stumps at the famous Carboniferous locality at the Joggins, Nova Scotia; Dawson published a number of later papers on additional finds. The material has been restudied by Miss Steen (1934) (who gives references to the earlier literature). Much of it pertains to a small

rhachitomous amphibian, *Dendropeton*, but in addition there are various more obscure remains to which a variety of names has been given. One named form is of importance here—the genus *Hylonomus*, with *H. lyelli* as the genotypic species. The type material is that of a small animal which Dawson believed to show reptilian affinities. For its inclusion he erected the group Microsauria. This term was retained by Cope (1869, p. 9) and by the Miall Committee in 1875; they, however, in opposition to Dawson, considered the Microsauria as amphibians rather than reptiles—an opinion followed by most (but not all) later writers.

Until this time, no forms other than those represented by Joggins material had been included in the Microsauria. Now, however, began Fritsch's classic studies of the fauna of the "Gaskohle" of Bohemia, the results of which were published in four quarto volumes beginning in 1879. Among the tetrapods from Nyran and other localities in the Stephanian of Bohemia were a number of small forms—as *Microbrachis*, *Hyloplezion*, *Seeleya*, *Sparodus*, "*Limnerpeton*"—which he associated with the Microsauria; in fact, certain remains were included in the typical genus *Hylonomus*. There followed Crédner's work on the equally famous European Lower Permian locality of the Plauen'schen Grunde near Dresden. Certain small tetrapods—"Hyloplezion," *Petrobates*—from this locality were interpreted by Geinitz and Deichmüller (1882) and by Credner (1885, 1890) as related to Fritsch's and Dawson's microsaurians and indeed one of the two forms concerned was assigned (on very slight grounds) by Credner to Dawson's genus *Hylonomus*. In this country, Cope described the fauna of the Linton (Ohio) cannel (1875, etc.); most amphibians from this deposit are labyrinthodonts, neotridians or aistopods, but many of the Linton forms have been referred at one time or another to the microsaurians (Moodie, 1916, Romer, 1930, Steen, 1981). Unpublished work by L. I. Price indicates that a number of small Texas Lower Permian tetrapods, often confused with the captorhinomorph reptiles, are related to the supposedly characteristic microsaurians—these including *Pariotichus* (s.s.), *Cardiocephalus*, *Gymnarthrus*, *Euryodus*, and possibly others. Still further forms have been assigned to the general micro-saur category by one writer or another. Most workers treating of this assemblage of forms have retained Dawson's name

Microsauria, although the writer (1933, pp. 112, 436) used Micramphibia as more appropriate. Watson (1929) in describing some small skulls from the Scottish Lower Carboniferous—*Adelogyrinus*, *Dolichopareias*—coined the new ordinal name Adelospondyli. This term, applied primarily to the Scottish genera and to *Lysorophus* of the American Permian, was mainly based on the fact that in these forms, in contrast to various other lepospondyls, neural arch and centrum are suturally separate. However, Miss Steen's work (1938) shows that this sutural situation is spread widely but sporadically and variably through much of the extent of the microsaur. As Westoll notes (1942a) the neurocentral suture proves to be an unreliable taxonomic character, and Adelospondyli appears to be essentially a synonym of Microsauria—as this term is currently used. Although various authors have made various additions or subtractions, the circle of forms currently regarded as belonging in the Microsauria is essentially that given by me in the recent edition of my text (1945a, pp. 591-592).

THE MICROSAUR CONCEPT

The current microsaure concept embraces a variety of tetrapods, mainly from the late Pennsylvanian but extending downward stratigraphically into the Mississippian and upward into the Lower Permian. All are of small size—many are tiny. All appear to have spool-shaped, "holospondylous"—i.e. lepospondylous—vertebral centra, and in this are in contrast with typical labyrinthodont amphibians. We may note that in distinction from other lepospondyls the vertebrae lack the peculiar fan-shaped caudal arches which are the trade-mark of the nectridian; the body shape, where known, is relatively normal and hence in contrast with the snake-like types currently placed in the Aistopoda (*Lysorophus* and its allies, if considered microsaur, are atypical in this as well as other regards). Beyond these few obvious features there is at present in the literature no further definition of a microsaure. This situation suggests that we are dealing with an amorphous, ill-defined assemblage with nothing to guarantee that it is a natural unit. Further, there is little to distinguish microsaur on this basis from the reptiles—a point of major importance, since confusion may occur (and has occurred) between the

two groups, and since at various times part or all of the microsaurs have been claimed to be reptiles or related to them.

We shall not at this point concern ourselves with the nature of the Nova Scotian *Hylonomus* "type" of the microsaurs, for, as we have noted, the concept of the group Microsauria rapidly passed from one based on *Hylonomus* to one derived from a series of forms, mainly European, which are not necessarily similar to *Hylonomus* (and, as noted elsewhere, are apparently quite distinct). Of such forms *Microbrachis* of the Stephanian of Nyran is the best known, since it is represented by abundant material which has been carefully redescribed by Miss Steen (1938, pp. 227-234, figs. 15-20, plates 1, 3). *Microbrachis* has certain characters of the skull table which are not repeated in other microsaurs and hence may be recognized as specializations; it otherwise appears to occupy a reasonably central position in the modern concept of a microsauro (and is so considered by Westoll, 1942b). Features seen in *Microbrachis* and its close allies which can be of aid in deciding whether or not other forms belong in the same broad category are here listed and commented upon.

1. *Size small.* The specimen restored by Steen has a length of about 12 cm.; some individuals of *Microbrachis* were moderately longer. This size appears to be about an average for Carboniferous microsaurs (some terminal Lower Permian forms were considerably larger).

2. *Body moderately long and slender.* *Microbrachis* and various other microsaurs have rather salamander-like proportions, with an elongate trunk (here about four times the skull length); a high number of presacral vertebrae (here 38 presacrals, but a somewhat lower count in other known cases); rib contours indicating a relatively narrow trunk.

3. *Spool-shaped vertebral centra; no trunk intercentra; caudal chevrons?; neural arch pedicel relatively high and narrow anteroposteriorly; neural arch not expanded transversely nor swollen; neural spine little developed.* The vertebrae and ribs of *Microbrachis* are figured by Steen (1938, fig. 19C) and Schwarz (1908, fig. 35). In various other microsaurs the centra may be less elongate; cf. for example, Fritsch, 1879, plate 40, fig. 1 (*Seeleya*). Trunk intercentra have not been reported in any form here regarded as a microsauro; it is, however, not impossible that such structures were present in

cartilage in some cases. Steen reports poorly preserved caudal chevrons in one specimen of *Microbrachis*. Since, however, they do not appear in other individuals of this or in related forms, and since some confusion with caudal ribs is not impossible in a small and poorly preserved specimen, judgment may be suspended on this feature. The narrow base of the neural arch and lack of any degree of spine development is a striking feature of Nyran microsaurs in general, as may be seen in various of Fritsch's figures on his plates 37, 39, 40, 44, etc. There is no evidence in the material of the expanded, swollen type of neural arch so typical of the cotylosaurs and of the seymouriamorphs.

4. *Ribs two-headed, capitulum often articulating with facet or low process on the centrum, tuberculum articulating with transverse process.*

5. *Interclavicle with very broad but short fan-shaped head and short slender stem.* The girdles are too poorly preserved in most microsaurs for accurate diagnosis. The interclavicle is, however, of a unique type; see Steen, 1938, fig. 19B; Fritsch, 1879, plate 47, figs. 1-8.

6. *Limbs relatively short and feeble; manus three-toed.* The limbs of *Microbrachis* and of such other typical microsaurs as have at all adequate limb material preserved are relatively short and slender compared with those of many labyrinthodonts and are seen to be especially feeble if compared with those of contemporary reptiles. That the three-toed nature of the manus of *Microbrachis* is not exceptional or based on faulty material appears to be confirmed by a similar three-toed condition in *Hylopleuron* (Steen, 1938, fig. 22A).¹

7. *Scales with a characteristic radiate striation; ventral scales sub-oblong, with a pronounced posterior ridge; dorsal scales rounded.* This type of radiate scale ornamentation is, as far as I am aware, confined to microsaurs and is widespread in this group. The scales of *Microbrachis* (Fritsch, 1879, plate 47) are slightly atypical in that the ridges of the striate pattern are heavier and coarser than is normal; for other and perhaps slightly more typical scales from Nyran, cf. Fritsch, 1879, plate 32, figs. 2, 5; plate 35, figs. 5-7; plate 37, figs. 1, 9-11; plate 39; plate 40; plate 41, figs. 2, 3, etc. In some cases (as

¹I know of no evidence for the restoration by Fritsch (1879, figs. 94, 103, 105, 108, 112) of microsaurs with a five-fingered hand.

Sparodus crassidens, Fritsch, 1879, plate 10) the pattern may assume a more circular rather than a radial arrangement.

8. *Skull greatly elongate postorbitally; otic notch absent.* In the series crossopterygians-amphibians-reptiles there has been, as pointed out by Westoll (1938) and the writer (Romer, 1941b, pp. 156-159, fig. 4) a notable shift in skull proportions as regards the relative length of the preorbital and postorbital segments; there has been, along this main evolutionary line, a steady reduction of the relative length of the postorbital region

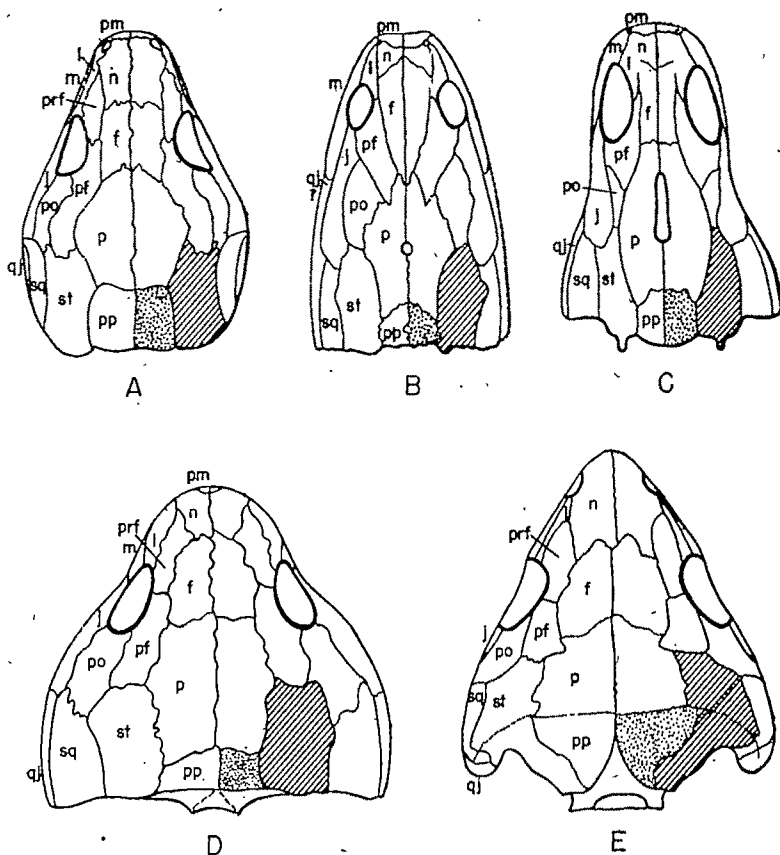


Figure 1. Dorsal views of various microsaurs: *A*, *Euryodus*, *B*, *Dolichopareias*, *C*, *Adelogyrinus*, *D*, *Pantylus*, *E*, *Ostodolepis*. Abbreviations: *f*, frontal, *j*, jugal, *l*, lacrimal, *m*, maxilla, *n*, nasal, *p*, parietal, *pf*, postfrontal, *pm*, premaxilla, *po*, postorbital, *pp*, postparietal, *prf*, prefrontal, *qj*, quadratejugal, *sq*, squamosal, *st*, supratemporal, *t*, tabular. On right side, supratemporal hatched, postparietal stippled. *A* after Olson, *B*, *C* after Watson, *D* composite of various specimens, *E* after Case.

(disregarding obviously secondary reversals among certain temnospondyl labyrinthodonts). The short face and long post-orbital region of *Microbrachis* (and other microsaurs) shows a remarkably primitive condition (figs. 1, 2).

9. *Skull roofing pattern generally primitive, but tabular absent from roof and a very large supratemporal interposed between parietal and squamosal.* The pattern of the temporal region, when preserved, offers the best diagnostic character of this group (figs. 1, 2). In various other amphibians—notably the Rhachitomi—there is a trend for reduction of bones on the skull table, so that in addition to loss of the intertemporal the posterior elements may undergo reduction at the expense of the more anterior ones. But in no known labyrinthodont is the tabular completely excluded from the skull roof; here it is absent in all known cases, although the postparietal persists dorsally. In contrast to the reduction of the tabular we find the supratemporal highly developed as a major component of the skull roof.

In regard to the skull table *Microbrachis* (fig. 2B) appears to be somewhat aberrant; such a form as *Euryodus* (fig. 1A) shows what is apparently a more primitive condition. In such forms the postparietals, strongly reduced in *Microbrachis*, are persistently large. Further, while the supratemporal is a large

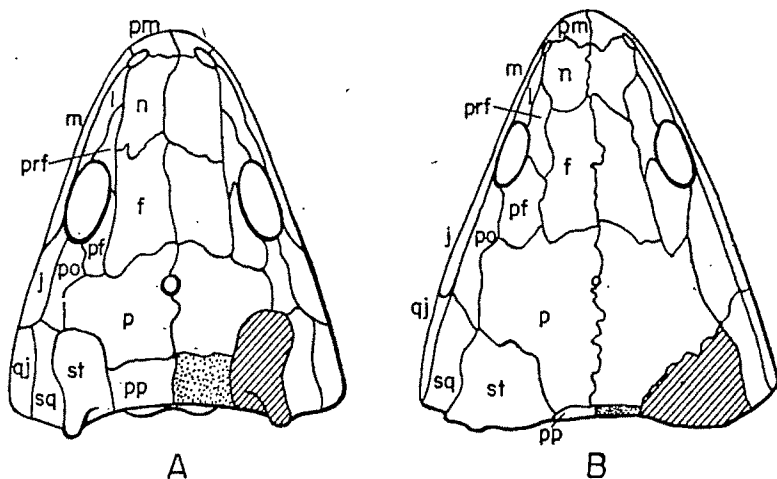


Figure 2. Dorsal views of skulls of *A*, *Hyloplexion*, *B*, *Microbrachis*. Abbreviations and conventions as in figure 1. *A* partly after Steen, posterior elements restored from Fritsch's data; *B* after Steen, but postparietal (present in smaller individuals only) retained.

element in *Microbrachis*, it is still more prominent in other microsaur shown in figs. 1 and 2, stretching forward to a broad contact with postfrontal and postorbital—a contact almost entirely lost in *Microbrachis*.

Whether the element here termed supratemporal is really that element or the tabular is not, of course, entirely certain (particularly in the absence of knowledge of the occiput in most microsaur). But presumably the process of modification in skull table pattern was parallel to that seen in certain labyrinthodonts, in which the tabular may be nearly pushed off the skull roof, while the supratemporal remains an element of substantial size (Romer, 1947, fig. 22, etc.). It is important to note that in these labyrinthodonts the postparietal is reduced *pari passu* with the tabular, whereas in microsaur the former element is much more resistant to reduction.

10. *Palate essentially primitive in nature, with slender cultriform process of parasphenoid; movable basal articulation of braincase and palate, narrow interpterygoid vacuities.* Unfortunately little is known of braincase structure in *Microbrachis* or indeed in any microsaur. The occipital condyle (unknown in *Microbrachis*) appears to have been generally primitive in nature—technically single, but broadened and trending (as in other amphibians) toward the double type.

The items listed above give us a diagnosis which may be applied to Paleozoic tetrapods as a possible test of inclusion in or exclusion from the microsaur group. It is unfortunate that this list of characters seen in *Microbrachis* is incomplete and to some degree superficial. However, the forms to be surveyed are in almost every case still more poorly known than is *Microbrachis* itself and we must grasp at any available straw. Of the characters listed, the skull table pattern is apparently most useful in cases where the skull is known; in fragmentary or poorly preserved material, the scale type is a useful clue.

IDENTIFIABLE MICROSAURS

1. *Microbrachis*, as discussed above.

2. *Hyloplecion*. In the late Pennsylvanian Gaskohle fauna of Bohemia described by Fritsch, a number of other microsaur are identifiable. Best known is *Hyloplecion longicostatum*, represented by complete skeletons as well as more fragmentary materials (Fritsch, 1879, pp. 160-161, plate 27, fig. 5; plate

36, fig. 2; plates 37, 38; plate 39, figs. 1-9; Steen, 1938, pp. 234-237, figs. 21, 22, 44B; plate 1, fig. 1; plate 4, fig. 3). In general the skull is quite similar to that of *Microbrachis*. Steen figures a small tabular, but this interpretation is certainly questionable and Fritsch's figures and galvanotypes strongly suggest that the supratemporal extended back to the posterior end of the table as in other microsaurs (fig. 2A). *Hyloplezion* is less specialized than *Microbrachis* in that the postparietals are well developed. The postcranial skeleton, including vertebral count and structure, squamation, etc., all agree well with *Microbrachis*. The presence of a three-toed manus, as in that genus, may be noted.

3. "*Limnerpeton*." This genus of Fritsch's is a dumping ground for poorly known amphibians. Some of the remains are those of labyrinthodonts (Romer, 1947, pp. 143-144) and some are quite obscure.³ A majority of the *Limnerpeton* species seem, however, to fit in well with the microsaur pattern in scales, vertebrae and other details. Such are: *L. macrolepis*, *L. elegans* and *L. obtusatum* (Fritsch, 1879, plates 32-35, etc.).

4. *Seeleya* (Fritsch, 1879, plate 40, fig. 1; plate 41, figs. 1-3). This is a very tiny Nyran form, obviously pertaining to this group but with relatively short vertebrae. *Orthocosta* (Fritsch, 1879, plate 39, figs. 10, 11; plate 44, figs. 1-3) is a probable synonym.

5. *Sparodus*. Somewhat more doubtful is this genus (Fritsch, 1879, plates 8-10). Two species are described; their congeneric nature is none too certain. *S. crassidens*, from Kounova, exhibits microsaur squamation. Both, but particularly *S. validus* from Nyran, have a strong palatal dentition which was compared by Cope (1881, p. 79) with that of *Pantylus* of the American Permian.

6. *Ricnodon*. The fragmentary material assigned to this genus by Fritsch (1879, pp. 167-171, figs. 106-108, plates 42, 43, 44, figs. 4-15) shows microsaur vertebrae and scales. However, the skull described by Watson and by Steen (1938, p. 227, figs. 13, 14, plate 7) as *R. limnophyes* is not microsaurian in nature and evidence for assignment here is very weak.

² "*Limnerpeton*" *laticeps* (Fritsch, 1879, plate 36, fig. 1) is strikingly similar to *Amphibamus* and *Miobatrachus*, presumed ancestral "frogs."

7. "*Hylonomus*" of Niederhässlich. Certain small tetrapods present in the early Permian Niederhässlich deposits near Dresden, first described by Geinitz and Deichmüller (1882, plate 8, figs. 1-9) were identified as belonging to Fritsch's genus *Hyloplezion*. Credner (1885, pp. 724-736, plate 29) assigned this material to Dawson's genus *Hylonomus* (quite incorrectly, one may believe); later, however, he realized that two quite distinct animals were represented. One, *Petrobates*, will be considered later; the second he termed *Hylonomus geinitzi* (Credner, 1890, pp. 240-247, 255-258, plate 9, figs. 1-11), pointing out, however, its close similarity to Fritsch's *Hyloplezion*. This animal (once the *Petrobates* material is sorted out) conforms in most regards to the typical microsaure structure defined earlier. The vertebrae and clearly dichotomous ribs are comparable to those of *Microbrachis* and *Hyloplezion*. Intercentra are absent; so too are haemal arches in the tail. Credner's plate 9, figure 5 indicates a vertebral count of close to 30 presacra (despite his own statement that the count was much lower). Several of Credner's figures show the characteristic fan of the interclavicle, and a low degree of development of limbs, much as in *Microbrachis* and *Hyloplezion*. The scales are closely comparable with those of *Hyloplezion*. It may be noted, however, that in addition this form has a series of tiny polygonal bony plates in the region of the pectoral girdle (Credner, 1890, plate 9, figs. 6, 9, 10, 's'). The skull is poorly preserved but Credner's plate 9, figure 6 shows clearly the presence of three elements lateral to the parietal—obviously the characteristic large supratemporal in addition to squamosal and quadratojugal.³

8. *The gymnarthrids*. Vertebrate specimens from the early Permian Redbeds of the American Southwest are preserved in a fashion quite different from those of the European deposits so far discussed. Instead of slabs of shale on which small skeletons may be preserved but skulls crushed, the usual matrix is a clay from which recovery of tiny skeletons is unusual but in which skulls may be preserved in three-dimensional fashion. In consequence we deal here mainly with skull material. Parenthetically, we may note that these terminal members of the

³ The restored composite skull figured as that of "*Hylonomus geinitzi*" by Watson (1940, fig. 11) does not agree with this; it is, however, of a type to be expected in *Petrobates*.

microsaur group tend (as do other contemporary lepospondyls) to relatively (although not absolutely) large size.

The typical microsaurs of the American Redbeds are a series of forms which include *Pariotichus*, *Gymnarthrus*, *Cardiocephalus*, *Euryodus* and *Isodectes*; they are known almost entirely from skull materials, these skulls averaging about 2 cm. in length. Most recently described is *Euryodus* (Olson, 1939); a resumé of the older material was given by Case (1911a, pp. 69-70, 144-145; 1911b, pp. 34-35, 36-38, 91-93). Mr. L. I. Price informs me, as a result of his unpublished studies of the group, that all are very similar in cranial structure despite variations in description. The skull pattern, as seen in *Euryodus* (fig. 1A) or *Pariotichus*, is exactly that to be expected in a typical microsaur—a short face, a very long, post-orbital region, good postparietals but no tabular in the skull table, and a long and highly developed supratemporal reaching forward to a broad contact with both postorbital and postfrontal. The palate, as in other microsaurs, is one with a narrow cultriform process of the parasphenoid, movable basal articulation and narrow interpterygoid vacuities. The teeth are, in this group, blunt and medio-laterally compressed. As in certain, at least, of the other microsaurs there is no indication of emphasis of the "canine" region in the anterior part of the maxilla; instead there is here a trend toward tooth enlargement in the posterior part of the maxillary series.

9. *Ostodolepis*. Other microsaurs, less typical in nature but definitely members of this group, can be identified in the Redbeds fauna. One such is *Ostodolepis*. This was first described by Williston (1913) on the basis of vertebrae; Case later (1929) described a nearly complete skeleton. A striking peculiarity lies in the skull shape, with a domed roof and curiously pointed "snout." Case, in summarizing the features of *Ostodolepis*, found himself puzzled to assign this form to either reptiles or amphibians since it seemed to him to show many features characteristic of both classes. However, the more important of his supposed reptilian characters—such as the palatal construction—are now known to be primitive amphibian characters retained in microsaurs as in reptiles.

The skull, despite its obvious peculiarities, shows the definitive microsaur characters (fig. 1E): absence of tabulars from the skull roof, but retention of postparietals (here slanting

backward on the occipital surface), and a highly developed supratemporal running from postorbital and postfrontal to the back of the skull. Ossified hyoids are present. The vertebrae are "holospondylous"; there are no intercentra⁴ nor is there space for them; the neural arches are not broadened nor swollen. The imperfectly preserved interclavicle has (Case notes) an extraordinarily broad head, and thus is probably of microsauro type. The limbs are relatively small. There is preserved a system of ossified scales which Case compares with those of the microsauro *Sparodus crassidens* of Fritsch.

10. *Pantylus*. The genus *Pantylus*, mainly known from skull material from the Texas Permian Redbeds, has long been a puzzle to paleontologists; Williston (1916, pp. 165-176) is the most recent describer. The lack of an otic notch and its relatively large size (reaching a skull length of 9-10 cm.) have caused most authors to place it among the cotylosaurs. It does not, however, conform readily to the structural pattern of any cotylosaur group, and its specialized dentition, with a battery of blunt crushing teeth, tends to further isolate it. Restudy indicates that it is unquestionably a (relatively) large end form among the microsaurs, and is obviously related to *Sparodus* of earlier European deposits (Cope, 1881, p. 79; Romer, 1945b, p. 429). The proportions of the skull roof are typically microsaurian. Williston was unable to determine the pattern of the skull table; comparative study of all available material indicates the presence of the microsauro pattern shown in figure 1D. As in other members of the group, the palate retains a movable basal articulation, and interpterygoid vacuities are small. Vertebrae presumably associated are comparable to those of *Ostodolepis*. If the caudal vertebrae figured by Williston are actually those of *Pantylus* they are of considerable theoretic interest in bearing haemal chevrons. The limbs, incompletely known, were very small; plates in the form of tiny tesserae covering part of the belly are comparable to those noted for the Niederhässlich "*Hylonomus*."

11. *Tuditanus*? Curiously, identifiable microsaurs from the Carboniferous are as rare in North America as they are abundant in Europe. Several forms thought to be microsaurs are (as noted later) true reptiles. Of the three major American

⁴ The supposed intercentra of Williston's type are not such but are apparently rib fragments.

Pennsylvanian tetrapod localities—Mazon Creek, the Joggins, and Linton—no microsaur are identifiable from the first and none is positively known from the second (although very probably present). Even at Linton there are few specimens which can even be considered for entry into this category, for most of the forms termed microsaur by Moodie (1916) have since been shown by Steen (1931) or the writer (1930, 1947) to belong elsewhere or are peripheral, rather than typical members of the microsaur group. The only specimens which merit consideration are the type of *Tuditanus punctulatus* and a second specimen which Cope assigned to this species but was made the type of *Eosauravus copei* by Williston (Cope, 1874, pp. 271-272; 1875, p. 392, plate 84, fig. 1; 1897, pp. 88-90, plate 3, fig. 1; Williston, 1908, pp. 395-400; Moodie, 1909, pp. 11-16, plates 4, 5; 1916, pp. 55-88, fig. 19; Romer, 1930, pp. 134-135, etc.). The type specimen of *T. punctulatus* consists of the anterior part of the body of a small tetrapod; the second, type of *Eosauravus*, includes much of the trunk and tail but lacks head and anterior limbs. The *Eosauravus* specimen was hailed by Williston as "the oldest known reptile" and is generally considered as reptilian; little attention has been paid to the *T. punctulatus* type, and there is no guarantee that the two are associated. Little can be made of the skull, and squamation is absent from both specimens. Evidence for reptilian nature is the assumed hind leg phalangeal formula of 2.3.4.5.4, possible presence of more than three digits in the manus and of two sacral ribs, and the presence of a stemmed interclavicle. But there is no evidence of five phalanges in toe four, and certain microsaur have a five-toed pes with nearly as high a formula; further, it is not impossible to interpret the interclavicle as of the peculiar type seen in *Microbrachis*, etc. Arguing for a microsaurian position are the long and slender body proportions; it is clear that both specimens of *Tuditanus* must have had a higher presacral count of vertebrae than is found in early reptiles. Again, caudal chevrons appear to be absent. Still further, if Moodie is correct as to orbital position in his figure of the *Tuditanus* skull, the long postorbital region is indicative of microsaur rather than reptilian structure. More evidence is needed, but *Tuditanus* is not improbably a microsaur.

12. *Dolichopareias*, *Adelogyrinus*. Among the few known

amphibians of Mississippian age are two types of modest size represented by skulls and in one instance by some postcranial remains including "holospondylous" vertebrae (Watson, 1929, pp. 245-250, figs. 24-27). In both genera (fig. 1B, C) the "face" is extremely short, the postorbital region much elongate, in a fashion both primitive and comparable with that of later microsaur. In correlation with this elongation, the postorbital bone has been dragged backward out of the orbital margin (cf. *Colosteus*, *Erpetosaurus*). In both (again as in microsaur) postparietals are well developed, but tabulars are absent from the skull roof. In both we find instead—as in microsaur—a single elongate element lateral to the parietal and postparietal extending from the postorbital to the back margin of the skull.⁵ In *Dolichopareias* the lateral margin of the cheek is unknown, but we can reasonably regard this element as the supratemporal and assume both squamosal and quadratojugal to have been present more laterally. In *Adelogyrinus* no suture is evident between supratemporal and squamosal, a single large element occupying the position of the two. These two genera may be reasonably considered as early forerunners of the microsaur.

The microsaur periphery. So far we have confined our survey to forms exhibiting, as far as can be determined, the characteristic features of the microsaur defined above. There are, however, various other lepospondylous forms of the Carboniferous and earlier Permian which may be allied to the microsaur and may perhaps be included in a broad common group with them. These may be noted in passing.

It will, I think, be generally agreed that the varied neotridians form a distinct category of lepospondyls. There remain, however, three further series of amphibians, all elongate eel-like or snake-like forms, which are lepospondylous but non-neotridian and hence possibly of microsaur affinities. The *Ophiderpeton* and *Dolichosoma* groups, of ancient lineage, but poorly known, are customarily included (for no particular reason) in a common, distinct group, the Aistopoda. A third series of elongate forms, of which *Lysorophus* of the early Permian is best known, is, in contrast, often included in the microsaur, and definitely included in Watson's Adelospondyli.

⁵ There is no positive evidence of a tabular, despite its restoration by Bystrow (1935).

Lysorophus, however, is a very specialized form which shows few of the features cited above as characteristic of the microsaurs (cf. J. T. Gregory, 1948a, p. 564) and there is as little—or as much—reason for its inclusion here as for the inclusion of the aistopods.⁶ If these forms are related to the typical microsaurs, as may well be the case, the relationship is a distant one and discussion of this matter is not pertinent to our present purposes.

TRUE REPTILES CONFUSED WITH MICROSAURS

It is obvious that the microsaurs have many features in common with the reptiles,—features which have led various people to advocate their relationship to reptiles or even their inclusion in that class. Putting aside for the moment the problem of possible relationship, it is of importance to see how a microsauro can be distinguished from forms which would be agreed to by all to be definitely reptilian. *A priori*, it is highly probable that confusion between two such groups, whether related or not, might readily take place. It was once thought that reptiles made their appearance at about the beginning of the Permian; but various instances of the occurrence of true reptiles are now known well down in the Carboniferous and the finding in the Pennsylvanian of such specialized reptile types as *Edaphosaurus* and diadectids indicates that the origin of the Reptilia is to be looked for well back in the Pennsylvanian. We must be on the outlook for small Carboniferous true reptiles which, if poorly preserved or insufficiently described, might be included among the microsaurs.

If the list of microsauro characters cited above be examined, it is obvious that certain of them are found both in this group and in forms generally accepted as genuine reptiles. Both have “holospondylous” vertebrae; the ribs are similar; the microsaurs, like reptiles, have retained an essentially primitive type of palate contrasting with that of most amphibians; neither typical microsaurs nor primitive true reptiles have taken on the eel-like proportions of certain amphibian types; most reptiles have, like microsaurs, eliminated the otic notch; typical microsaurs are much smaller than the average of known early reptiles, but size is no safe criterion.

⁶ As I hope to show at another time, *Lysorophus*, sometimes thought to be an ancestral urodele, is a reasonable ancestor of the Apoda.

Other features may, nevertheless, aid us in distinguishing between the two groups. On the basis of present knowledge, the presacral intercentra are indicative of a reptile rather than a microsauro, and the presence of haemal arches is perhaps diagnostic as well. Early true reptiles are all relatively short and stocky, with no more than 27 presacral vertebrae, and with stoutly developed limbs; all microsaurs in which the body form is known have much more slender and elongate trunks, with a higher presacral vertebral count (usually in the 30s) and with limbs of smaller size.⁷ The pes of microsaurs is of a pentadactyl type not dissimilar to that of reptiles; the manus, in contrast, has but three digits in known instances.

The squamation is highly distinctive. The typical microsaurs have well developed ornamented ventral (and dorsal) scales; in reptiles there is a ventral "abdominal rib" system with the scales reduced to oat-shaped or rod-shaped elements.

The skull, if well preserved, can exhibit strongly contrasting features (cf. fig. 3 with figs. 1, 2). The microsauro skull is exceedingly primitive in its elongate postorbital region; reptiles are notable for major reduction proportionately of the

⁷ Even discounting the greater slenderness of limb elements to be expected in small animals.

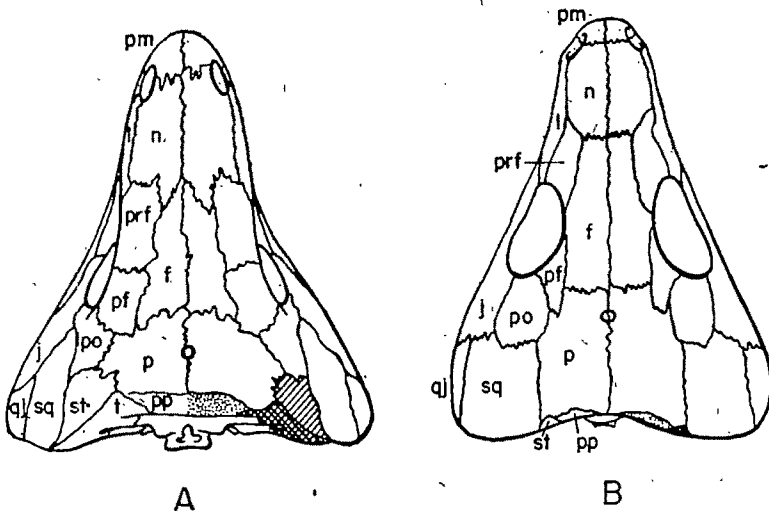


Figure 3. Dorsal views of skulls of captorhinomorph cotylosaurs: *A*, *Limnoscelus*, *B*, *Captorhinus*, to show contrast in skull pattern with that of microsaurs. Abbreviations and conventions as in figures 1 and 2; tabular cross-hatched.

posterior skull region. In microsaurs the otic notch has been obliterated—so thoroughly obliterated that dermal cheek and table elements are welded into a single unit. In early reptiles the notch is still retained in diadectomorphs; it is lost in captorhinomorphs, but welding of cheek and table is still imperfect, so that, as seen in *Limnoscelis* (and even in pelycosaurs) there persists a line of structural weakness between cheek and table components. The condition of supratemporal, tabular and postparietal is markedly different in the two groups. In reptiles in correlation with occipital shortening, the table exposure of both postparietal and tabular is much reduced and the supratemporal, never of great size, is reduced in parallel fashion. In microsaurs, the condition of these three elements differs greatly. The tabular is completely eliminated from the roof in every known instance, while in every form known except *Microbrachis* the postparietal remains well developed dorsally. The supratemporal is not reduced concomitantly with the posterior elements; instead, it is expanded to become a very prominent element in the pattern.

Using these diagnostic characters, it can be seen that certain forms often included in the microsaurs do not fall in this group, but are apparently proper reptiles, presumably cotylosaurs.

1. *Petrobates*. This name was applied by Credner to a small tetrapod from Niederhässlich which had earlier been confused by Geinitz and Deichmüller (1882, pp. 38-41) with "*Hylonomus*." Credner (1890, pp. 255-257) tabulates various differences between the two; and it is interesting that most of the features in which *Petrobates* differs from its contemporary are almost precisely those in which a primitive reptile might be expected to differ from a microsaurian amphibian (the skull structure is, unfortunately, poorly known). Both are small tetrapods with "holospondylous" vertebrae, but *Petrobates* is much the more stocky type, with stouter limbs and a shorter vertebral column (only about 19 presacrals as compared with a much higher number in "*Hylonomus*"); the manus is pentadactyl; haemal chevrons are present. A superficial but definitely diagnostic feature lies in the nature of the ventral squamation. Primitive reptiles as noted above are characterized by the presence of a system of V-shaped rows of slender oat-shaped or rod-shaped scales which contrast sharply with

the typical oblong amphibian scales of the microsaur. Reptilian scales are present in *Petrobates*; "*Hylonomus*" has the microsaure type. It seems certain that *Petrobates* is a small reptile, very probably a captorhinomorph cotylosaur.

2. *Cephalerpeton*, a small tetrapod from the nodule beds of Mazon Creek, was described by Moodie as a microsaure. The specimen has been restudied by J. T. Gregory (1948a). On the basis of its structure, he argues that *Cephalerpeton* is a reptile and that hence microsaurians are reptiles. With his conclusion that *Cephalerpeton* is a reptile I am in complete agreement. But many of the features which he cites to prove its reptilian nature are crucial reptilian characters not found in typical microsaurians. The slender ventral abdominal ribs are typically reptilian and in contrast with microsaure scales. Presacral intercentra are present in the column in contrast to known microsaurians. The limbs are more highly developed than in microsaurians and in contrast to microsaurians in which the manus is known, the front foot is pentadactyl. In apparent contrast with microsaurians (but the evidence is poor) is the presence of a distinct coracoid ossification and of an entepicondylar foramen in the humerus. Significant is the reptilian nature of the ventral scales as elongate gastralia. The skull proportions, with a much abbreviate postorbital region, are those of a reptile and in sharp contrast to those of true microsaurians. It is unfortunate that the skull table is poorly preserved but it seems certain that the most diagnostic of all microsaure features—the large supratemporal—is absent from the skull pattern. Significant as well is the typical reptilian pterygoid flange described by Gregory, and the pronounced retroarticular process of the jaw. Altogether, *Cephalerpeton* appears to be a true reptile, quite unlike the typical microsaurians, and presumably a member of the captorhinomorph cotylosaurians (cf. *Romeria*). The only contradictory evidence is the fact that the neural arches do not appear to show the swollen condition normally found in cotylosaurians.

3. *Hylonomus*, type of the Microsauria of Dawson (although not of later writers), is known only from the erect trees of the Joggins—and very poorly known at that, for, as Steen (1934) points out, there is no guarantee that any of the material assigned to this genus properly belongs here apart from the type specimen and a second which is closely comparable. Both are very fragmentary and there is no skull.

definitely associated. Even so, a variety of features indicate that we are dealing with a typical reptile. These include: (1) relatively large limbs; (2) caudal chevrons; (3) pelvis almost identical with that of such primitive reptiles as *Limnoscelis* (or even the pelycosaur *Ophiacodon*); (4) interclavicle of typical reptilian shape and especially (5) the scales, which are long slender rods of reptilian type and contrast strongly with those of the microsaur of current concepts. *Hylonomus* is probably a captorhinomorph cotylosaur but might possibly be an ophiacodontoid pelycosaur.

Fritschia and *Leiocephalikon*, likewise from the Joggins, are equally poorly known (Steen, 1984, pp. 490-492), but the evidence suggests that they also are true reptiles.

The identification of *Hylonomus* as a true reptile leads to an embarrassing situation in nomenclature, for the term Microsauria was based upon this genus. If we were dealing with nomenclature on a generic or specific level, this would mean that the name Microsauria should follow its "type" and that some other term should be used for the forms discussed in this paper. But there is no "legal" compulsion upon one to do this; no advantage would be gained and, on the contrary, some confusion would result. I therefore propose to continue the use of the term Microsauria in its current sense, based upon *Microbrachis* and related forms.⁸

4. *Eusauropleura*. A specimen from the Linton Pennsylvanian sometimes considered a microsauro is that which forms the type of *Eusauropleura* (*Sauropleura*) *digitata* (Cope, 1875, p. 403, plate 37, fig. 1; Romer, 1930, pp. 135-136, fig. 26, etc.). The specimen exhibits the ventral side of the trunk of an animal, showing the ventral squamation, much of the limbs and ribs. The head is not preserved, the vertebrae are not visible and the hind leg is incomplete. Such data as can be obtained indicate that *Eusauropleura* is a true reptile: (1) the oat-shaped gastral plates are of reptilian type, (2) the five-toed manus with a reptilian phalangeal formula of 2.3.4.5.3 is in contrast with the three-toed condition in known microsauria, (3) the trunk was obviously relatively short and compact, after the primitive reptilian rather than the microsaurian pattern.

⁸ I have profited from discussion with Dr. J. T. Gregory of this problem and others connected with the microsauria.

MICROSAURS AS REPTILE RELATIVES?

Even if we can distinguish morphologically between microsaurs and forms definitely reptilian, may it not be that these forms can still be classed as reptiles in a broad sense or as forms ancestral to them? Many workers have claimed that the microsaurs are of reptilian nature, as, for example, Dawson (1863, p. 47, etc.), Baur (1897), J. T. Gregory (1948a), Huene (1948). But if the conclusions given in the last section are accepted, the arguments of the first three of the writers mentioned are, while perfectly acceptable, beside the present point, for they are based almost entirely on forms—*Hylonomus*, *Petrobates*, *Cephalerpeton*—which appear to be true reptiles and not microsaurs in the customary sense.⁹ Huene's thesis rests in great measure upon certain features of rather doubtful or debatable nature, such as the presence of caudal chevrons, the identification as a tabular of the bone here called the supratemporal, presence of single occipital condyle, and of an otic notch.

⁹ Baur's evidence for the reptilian nature of "*Hylonomus*" (of *Niederhässlich*) as well as *Petrobates*—two sacral ribs, for example—appears to rest on specimens identified by Credner as belonging to the latter genus.

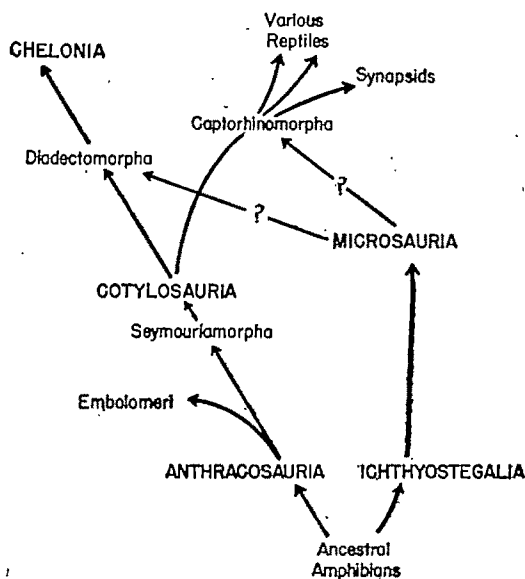


Figure 4. Phylogenetic diagram of possible origin of reptiles. Orthodox interpretation, through anthracosaurian labyrinthodonts, at the left; microsaurian derivation at the right.

Westoll (1942a, 1942b), from a somewhat different viewpoint maintains that the microsaurs, or adelospondyls, are ancestors of the captorhinomorph cotylosaurs. To properly evaluate his ideas it is necessary to view them in the light of currently accepted concepts of reptilian ancestry and phylogeny which have grown up through the work of Case, Williston, Watson and others (cf. fig. 4).

It is generally held that the reptilian pedigree stems from a point near the base of the Amphibia and leads through the anthracosaurian labyrinthodonts (these including the embolomeres) which had developed true centra and other reptile-like structures. *Seymouria* is a late representative of a group of anthracosaurs, or at least of forms of anthracosaurian derivation; it shows so many characters identical with those of reptiles as to be frequently included in the "stem reptiles" or, if not so included, is deemed ancestral to them. The reptilian basal stock is usually considered to form an ordinal group Cotylosauria. Known cotylosaurs, however, can be clearly divided into two groups, Diadectomorpha and Captorhinomorpha, as pointed out by Watson (1917) and emphasized by Olson (1947), who even argues that the two groups are so distinct that the term Cotylosauria should be abandoned. Both Olson and W. K. Gregory (1946) conclude that the turtles are descended from diadectomorphs and it is generally agreed that most, at least, of the other reptilian orders have sprung from the captorhinomorphs. Seymouriamorphs, diadectomorphs and captorhinomorphs differ in certain cranial structures, notably as regards the otic notch and adjacent elements, and the palate. *Seymouria* retains the primitive otic notch, diadectomorphs have a peculiarly exaggerated notch, captorhinomorphs have lost it; diadectomorphs have a specialized palate and dentition. In almost every other regard, however, the three groups are strikingly similar and many postcranial structures—even details of neural arch construction—are practically identical. It is difficult to escape the conclusion that the three are closely related, that the reptiles are monophyletic, and that their line of descent lies through the anthracosaurian labyrinthodonts.

Westoll's hypothesis is that the captorhinomorphs have descended from microsaurs (adelospondyls); that the seymouriamorphs are not phyletically related to reptiles; and

that while the seymouriamorphs are good anthracosaurs, both diadectomorphs and captorhinomorphs (via the microsaurs) have descended from the very ancient ichthyostegalians—very different amphibians indeed. Positive and convincing proof is required if one is to deny the seemingly certain relationship of *Seymouria* to the reptiles and establish a radically different line of reptilian ascent—proof which Westoll does not furnish. He cites the presence of certain microsaureptile similarities, attempts to bring limb structure of microsaurs in line with that of reptiles, and compares the captorhinomorph skull table structure with that of microsaurs. The presence of certain similarities between microsaurs and true reptiles is obvious; but these similarities are matched by still greater similarities between seymouriamorphs and reptiles and counterbalanced by differences which do not for the most part exist between reptiles and their presumed anthracosaur relatives. Limb comparisons force upon him the doubtful assumption that *Eusauroplorea*, *Hylonomus*, and *Fritschia* are microsaurs related to *Microbrachis*. It is possible, perhaps, to evolve the skull pattern of reptiles from that of microsaurs, but it is a hard struggle. Captorhinomorphs exhibit the general reptilian trend toward a shortening of the skull table; microsaurs are persistently primitive and show absolutely no trend of this sort. In the captorhinomorphs, postparietal, tabular and supratemporal show concomitantly the expected reptilian drift in skull table structure—posterior movement and reduction in size. Not so in microsaurs, for while the tabular is eliminated in all known microsaurs, the supratemporal has expanded to unusual size and the postparietal generally resists reduction. I can think of no Paleozoic amphibian forms (except for some of the eel-like lepospondyls) which, on the basis of skull table structure, are more unlikely reptile ancestors than the microsaurs. It is true that captorhinomorphs and microsaurs have in common one advanced feature in this region of the skull—elimination of the otic notch. However, this creates more difficulties than it solves; for, unless reptiles are (most improbably) polyphyletic, it involves development of the diadectomorph notch in secondary fashion. I have tried (1946) to explain how this might have happened; but my attempted explanation has not, I think, been satisfactory to my colleagues (nor, indeed to myself).

THE PHYLOGENETIC POSITION OF MICROSAURS

As to the ancestry of the Microsauria, descent from the ancient ichthyostegids is not unreasonable. Westoll (1942b) has advocated this pedigree, and I had independently reached the same conclusion. The evidence is, of course, incomplete and based essentially on the skull roof pattern and proportions. The postcranial skeleton of ancestral ichthyostegids has not been described. It is highly improbable that they had "holospondylous" vertebrae, but this is no bar to microsauro derivation, for it is obvious that vertebrae of this sort have arisen more than once among amphibian groups.¹⁰

In the discussion above, our attention has been concentrated on "typical" microsaurs. The question of the relationships to them of various specialized holospondylous types of the Paleozoic—the *Lysorophus*, *Ophiderpeton* and *Dolichosoma* groups, particularly—is worthy of further study, although it is probable that firm conclusions must await the discovery of new materials.

If reptilian relationship be denied, are the microsaurs terminal members of their line, or are they, in some sense or other, to be considered as ancestral to any later amphibians? As noted earlier, *Lysorophus*, a member of the microsaurian "periphery," is a possible ancestor of the Apoda. This form is often considered to be an ancestral urodele. It is, one would think, too far gone in body elongation and limb reduction to be seriously thought of in this light. But may not some other microsauro have to be the urodele ancestor? In most regards the "typical" Microsauria are reasonable urodele ancestors. The one strong objection lies in the palatal structure. The urodele palate was unquestionably formed by modification from a primitive amphibian type, with small interpterygoid vacuities and a movable articulation with the braincase. But one would expect late Carboniferous or early Permian ancestors of the urodeles to exhibit a trend in the modern direction (such as is shown in contemporary labyrinthodonts and even *Lysorophus*). The typical Microsauria show no such trend; on the contrary they are persistently primitive in this regard.

¹⁰ Note that even among the stereospondyls the brachyopids have evolved a "holospondylous" centrum by elaboration of the intercentrum.

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STANDARDS FOR GRADING TEXTURE OF EROSIONAL TOPOGRAPHY

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ABSTRACT. A study of texture, or drainage density, of stream-eroded topography was made to derive a ratio which will grade the texture on contour topographic maps and to establish limiting values of this ratio for "coarse," "medium," and "fine" texture. Standard values are suggested for the three texture grades, based on the application of the derived texture ratio to type areas. The term "ultra-fine texture" is used to designate the extremely fine dissection of badland topography. A comparative study shows that the texture ratio is a logarithmic function of R. E. Horton's "drainage density." It is hoped that these standards will prove of value in later quantitative geomorphic studies in which causative factors are being related to land forms.

INTRODUCTION

"**T**EXTURE of topography" was defined by Douglas Johnson (1938) as the "average size of the units composing a given topography." The term is here restricted to the description of regions dissected by streams, and is an expression of the spacing of the smallest drainage lines, both intermittent and perennial, whether or not these are represented on the map by symbols. It is therefore essentially synonymous with "stream frequency" (Horton, 1945), measured in terms of the number of stream channels per unit area.

Following a quantitative approach to geomorphology, a study of topographic texture, or drainage density (defined hereafter), was undertaken with the objective of deriving a ratio to grade the texture on contour topographic maps and of establishing limiting values of this ratio for "coarse," "medium," and "fine" textured topography. Standard United States Geological Survey topographic maps, on the scale of 1/24,000, were used for the study. Only recent maps of large scale can be relied upon to indicate all significant stream channels, both perennial and intermittent. In the present study, where data are taken from maps, emphasis must be placed on the necessity of using recent and accurate maps of the largest scale available.

The texture of topography depends upon a number of variable factors which may be divided into two classes: natural factors and map factors. Of the natural factors the most im-

portant are climate, vegetation, rock or soil type, rainfall intensity, infiltration capacity, relief, and stage of development. In general, weak rocks, unprotected by vegetation, produce fine texture; massive, resistant rocks cause coarse texture. Sparse vegetation of arid climates causes finer textures than those developed on similar rocks in a humid climate. Textures tend to be coarse in the initial and early stage of the erosion cycle; finest in early maturity when relief is greatest. Map factors affecting texture include the scale of the map and the accuracy of the mapping.

STREAM FREQUENCY AND DRAINAGE DENSITY

Two ratios which have been used to express the texture of topography are "stream frequency" and "drainage density," derived by R. E. Horton (1945).

"Stream frequency" is defined as the number of streams per unit area in a given drainage basin and may be expressed by the equation $F_s = N/A$, in which F_s represents stream frequency, and N equals the total number of streams in a drainage basin of A areal units.

"Drainage density" is defined as the length of streams per unit area in a given drainage basin and may be expressed by the equation $D_d = \Sigma L/A$ in which ΣL represents the total length of streams and A represents the area, both in units of the same system.

The term "texture" has been used in much the same sense as both "drainage density" and "stream frequency." However, values of drainage density and stream frequency for small and large drainage basins are not directly comparable because they usually vary with the size of the drainage area. A large drainage basin may contain as many small, or fingertip, tributaries per unit area as a small drainage basin, and in addition it usually contains a larger stream or streams. This effect may be masked by the increase of drainage density and stream frequency in the more rugged headward parts of the drainage basins.

DERIVATION OF THE TEXTURE RATIO

Testing of several possible texture ratios resulted in selection of the ratio of the number of crenulations on that contour having the maximum number within the drainage basin to the length of the perimeter of the basin. Each sharp outward bend in the contour is considered to represent a stream channel and

therefore to reflect the actual spacing of the drainage lines even though they are not shown on the map as individual streams.

This texture ratio is expressed by the equation $T=N/P$, where T represents the texture, N is the number of crenulations on the selected contour, and P is the length of the perimeter of the basin given in miles or fractions thereof.

Figure 1 illustrates the method of applying the equation. The hachured contour is the contour having the maximum number of crenulations. This contour commonly cuts the perimeter of the basin on opposite sides at points in the lower half of the basin. The dotted line indicates the perimeter of the basin traced around the divide. Length of perimeter may be measured with a chartometer.

DESCRIPTION OF LOCALITIES

Two general areas were selected for testing the texture ratio; one in southern California, the other in north-central Pennsylvania. Selection was made on the basis of the appear-

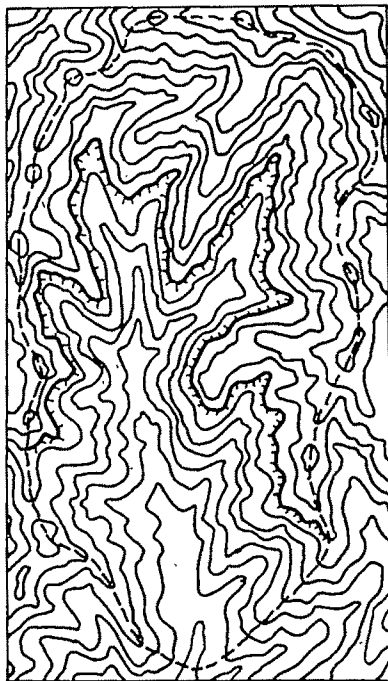


Figure 1. On the drainage basin outlined by dashed line the contour having the maximum number of crenulations is shown by hachures.

ance of fineness of dissection as observed on the topographic maps.

The California region was chosen as a possible type area for the grades of texture judged to be illustrations of medium and fine grades. Portions of four United States Geological Survey quadrangles, on a scale of 1/24,000, were used: Sunland, Altadena, La Crescenta, and Little Tujunga. The climate in this region is of the Mediterranean type with major rainfall in the winter and with very dry summers. Vegetation is a sparse chaparral which affords only moderate protection to the surface. The geology of the area is quite complex, but within small areas used here there is a similarity of land forms and drainage basins. One area, confined to the Verdugo Hills and including portions of the Altadena, Sunland, and La Crescenta quadrangles, is underlain by the Wilson diorite and the San Gabriel meta-sediments. That part of the Little Tujunga quadrangle in the vicinity of Kagel Canyon, which was used as representing fine texture is underlain by weak Pleistocene sediments, the Temescal and Victor formations.

The Pennsylvania locality was selected as a possible type area for coarse-textured topography. Three United States Geological Survey quadrangles, on the scale of 1/24,000, were used: Driftwood, Sinnemahoning, and Cameron. The climate here is a humid continental type with fairly uniform precipitation distribution and a coniferous-deciduous forest cover. The underlying strata of this part of the Appalachian Plateau are approximately horizontal and consist largely of resistant coarse-grained sandstones.

The size of the individual drainage basins varied greatly in the two regions. In the California areas the lengths of basin perimeters varied from 0.59 miles to 2.48 miles; in the Pennsylvania area from 2.3 miles to 6.61 miles in length. The basins were, however, similar in that the master streams are of the second or third orders (Horton, 1945, p. 281). Thus the samples are of comparable units of drainage networks.

The intricate dissection and strong relief in the California localities were such that it was necessary to enlarge the maps photostatically to the scale of 1/6000 in order to make accurate counts of the contour crenulations. Study of the Pennsylvania area was, however, made directly from the original maps.

VALUES OF THE TEXTURE RATIO

The texture ratio was obtained from forty-five small drainage basins; thirty in California and fifteen in Pennsylvania

TABLE 1
Texture ratio data for the Pennsylvania and
California localities.

	P (miles)	N	N/P	Area (sq. mi.)	ΣL (miles)	$\Sigma L/A$
Driftwood, Pa.	2.90	7	2.41	.516	3.25	6.30
	3.61	9	2.49	.599	2.91	4.86
	2.90	7	2.41	.463	2.00	4.14
Sinnemahoning, Pa.	5.20	17	3.25	1.670	6.59	3.94
	6.61	21	3.17	2.836	8.45	3.65
	8.90	9	2.30	.783	2.84	3.63
	2.30	7	3.04	.373	2.20	5.88
	3.00	12	4.00	.577	3.33	5.76
Cameron, Pa.	2.30	6	2.60	.347	1.17	8.37
	8.90	8	2.05	.757	2.24	2.95
	5.43	8	1.47	1.063	4.05	3.81
	3.40	4	1.17	.605	2.19	3.62
	3.70	11	2.97	.721	3.42	4.73
	3.29	7	2.12	.577	2.42	4.18
Sunland, Calif.	3.98	11	2.78	.742	2.65	3.58
	.89	10	11.22	.049	1.70	34.50
	.96	8	8.83	.050	.85	17.00
	1.36	15	11.08	.118	2.28	19.20
	1.29	11	8.52	.088	1.77	22.10
	1.53	10	6.53	.119	2.01	16.90
	1.01	9	8.91	.086	1.18	21.10
	.75	5	6.61	.027	.53	19.70
Altadena, Calif.	.81	8	9.87	.082	.93	29.30
	1.38	12	8.70	0.80	1.34	16.70
	1.54	21	13.63	.128	2.30	17.80
	1.62	17	10.49	.181	2.74	15.20
	1.05	7	6.66	.060	.98	16.40
	.95	4	4.21	.050	.85	17.10
	1.18	10	8.47	.086	1.40	16.30
	1.31	13	9.92	.094	1.47	15.60
	.83	7	8.43	.045	.68	15.20
	1.07	9	8.41	.056	.93	16.70
La Crescenta, Calif.	1.33	7	5.26	.079	1.50	18.90
	2.02	14	6.93	.205	4.12	20.20
	2.08	19	9.13	.244	4.10	16.80
	2.48	21	8.46	.319	5.53	17.40
	1.66	9	5.42	.139	2.22	16.00
	1.05	8	7.61	.063	1.19	18.90
Little Tujunga, Calif.	1.80	31	23.84	.096	3.13	32.60
	.75	17	22.72	.032	1.17	86.60
	.88	14	15.90	.044	1.37	81.10
	1.02	11	10.78	.052	1.38	26.60
	.69	13	18.84	.023	.76	34.00
	.59	6	10.16	.014	.50	35.90
	.75	9	12.32	.032	.90	28.10

(table 1). Values for N/P in the California localities varied from a low of 4.2, for one drainage basin in the Altadena quadrangle, to a high of 23.8 for one basin in the Little Tujunga quadrangle. For the region in north-central Pennsylvania values for N/P varied from a low of 1.1 for one basin in the Cameron quadrangle to a high of 4.0 for one basin in the Sinnemahoning quadrangle.

In addition to determining the texture ratios of individual drainage basins it is necessary to establish a mean value for N/P which will describe the texture of each area as a whole. The size of individual drainage basins must be taken into consideration when determining the mean value of the texture ratio, because the same weight cannot be attached to the texture ratio of a small drainage basin as to a large one. The weighted mean value for the topographic texture in a given region may be taken as the ratio of the sum of the products of the basin area times the texture ratio for each basin to the sum of the areas of the basins. This may be expressed by the equation $T_m = \Sigma(AN/P) / \Sigma A$, in which Σ represents the sum, A represents the area for each individual drainage basin, and N/P is the texture ratio for each basin as previously defined. In this manner final values for T_m are weighted according to size of the various drainage basins included.

Table 2 gives values of T_m for the seven quadrangles studied, listed in the order of increasing magnitude and calculated from the data of table 1. Mean values did not approach the lowest value for N/P of 1.1 for one basin in the Cameron quadrangle, nor did they approach the highest value obtained in the Little Tujunga quadrangle for N/P of 23.8. The results are believed consistent enough within each area to be used in establishing standards for grading topographic textures.

TABLE 2
Mean values of the texture ratio for the Pennsylvania
and California localities:

	ΣA (sq. mi.)	$\Sigma(AN/P)$	T_m
Cameron, Pa.	4.812	10.151	2.10
Driftwood, Pa.	1.598	3.899	2.43
Sinnemahoning, Pa.	5.739	18.075	3.14
La Crescenta, Calif.	1.049	7.996	7.62
Sunland, Calif.	.539	5.087	9.43
Altadena, Calif.	.780	7.460	9.56
Little Tujunga, Calif.	.293	5.245	17.83

PROPOSED STANDARDS FOR GRADING TOPOGRAPHIC TEXTURE

Based on values of T_m the following standards for grading the classes of topographic texture are proposed: For coarse-textured topography, T_m is below 4.0. A medium-textured topography may have a value ranging from 4.0 to 10.0. A fine-textured topography will have a value above 10.0.

These standards would place the Appalachian Plateau area of resistant sedimentary strata in the coarse-textured division. Of the California localities, those in the Verdugo Hills on Wilson diorite and San Gabriel meta-sediments would be classified as medium-textured, while the Little Tujunga locality, underlain by very weak Pleistocene sediments, would be classified as fine-textured.

ILLUSTRATIONS OF THE THREE TEXTURE GRADES

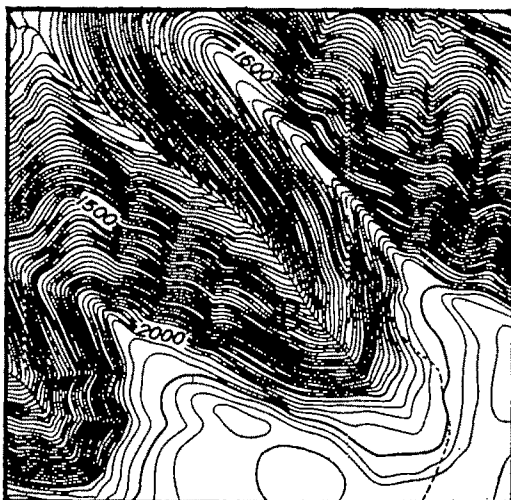
Maps have been prepared to demonstrate the appearance of basins having the three texture grades proposed in this paper (figs. 2, 3, 4). Each map shows one square mile for a visual comparison of the textures.

The first illustration, figure 2-A, shows a small drainage basin, Horsehead Hollow, in the Driftwood, Pennsylvania, quadrangle. This is a region of coarse-textured topography; the value N/P for this basin is 2.4. The mean value for the texture ratio of the area is also 2.4. The basin has only one main stream with two or three possible intermittent tributaries. A drainage map of this area, figure 2-B, in which the contours have been omitted, shows the scarcity of channels in an area of coarse texture.

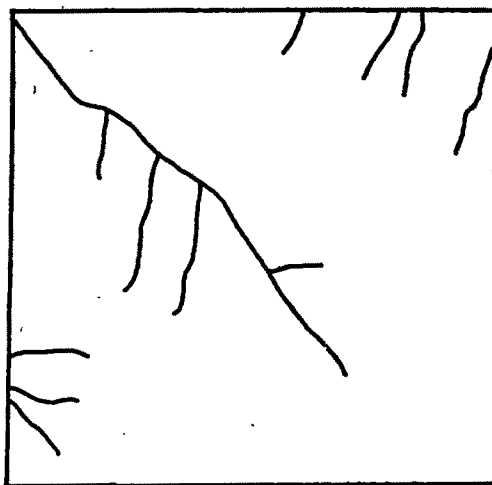
An illustration of medium-textured topography is taken from the La Crescenta, California, quadrangle, in the vicinity of Cunningham Canyon. (fig. 3-A). The value of N/P for the basin drained by Cunningham Canyon is 5.4, whereas the mean value for the texture in the Verdugo Hills on this quadrangle is 7.6. Figure 3-B, showing the possible stream channels as indicated by the contour crenulations, illustrates the increase of drainage density corresponding to the increase of the texture ratio.

The southwest portion of the Little Tujunga, California, quadrangle, in the vicinity of Kagel Canyon, is a very good example of fine-textured topography (fig. 4-A). The main basin shown, which drains to the south, has a value of N/P

=23.8. The mean texture ratio in this portion of the quadrangle is 17.8. The drainage map (fig. 4-B) shows that the region has a much higher drainage density than the medium-textured area.



A.



B.

Figure 2. Coarse texture. A. Topographic map. B. Drainage map.

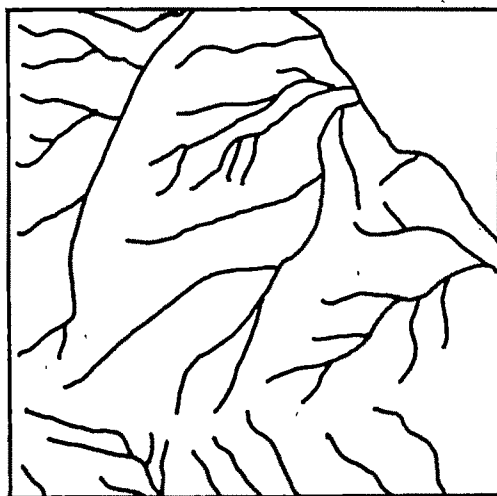
Figure 5 shows medium-and coarse-textured areas on two common scales: 1/31,680 and 1/63,360. These can be used for comparison with standard United States Geological Survey topographic maps.

ULTRA-FINE TEXTURES

The extremely fine textures of badlands on weak clays or



A.



B.

Figure 8. Medium texture. A. Topographic map. B. Drainage map.

marls cannot be adequately shown on the topographic maps of the scale 1/24,000 or smaller. Nevertheless these types are a part of the texture-drainage density series and must be analyzed, even though special maps must be made on an appropriately large scale. The term "ultra-fine texture" is here ap-



A.



B.

Figure 4. Fine texture: A. Topographic map. B. Drainage map.

plied to such badlands. The texture ratio was measured in two badland areas; one a dissected clay-sand back-fill near Perth Amboy, New Jersey, the other in the Petrified Forest, Arizona.

In the Perth Amboy locality six small basins were measured from a special topographic map prepared in 1948 by Professor A. N. Strahler and Mr. Donald R. Coates, of Columbia University, as part of a project to study the erosional development of badland topography. The scale of the map is 1/120; the contour interval is one foot.



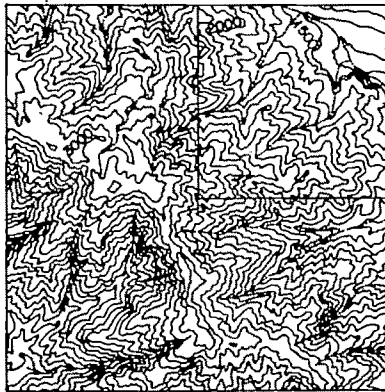
A.



A.



B.



B.

Figure 5. Illustrations of coarse and medium-textured topography at two common scales. A. Coarse texture, 1/31,680 and 1/63,360. B. Medium texture, 1/31,680 and 1/63,360.

This unusual area has an intricate drainage network developed on a homogeneous mixture of sand and clay, which has an extremely low resistivity to erosion and a low infiltration capacity. Although the area is in a region having a humid-temperate climate, there is no vegetation. Texture ratios for the six basins measured vary considerably, but are all greater than 100. The values may be compared from table 3, the lowest value of N/P being of the order of 139; the highest, 278.

TABLE 3
Texture ratio data for the Perth Amboy, N. J.,
and Petrified Forest, Arizona, localities.

	P (miles)	N	N/P	Area (sq. mi)	ΣL (miles)	$\Sigma L/A$
Perth Amboy, N. J.	.0216	3	139	.0000195	.0118	605
	.0180	5	278	.0000160	.0130	810
	.0204	4	196	.0000190	.0160	842
	.0236	6	254	.0000258	.0218	845
	.0184	4	218	.0000195	.0133	680
	.0163	4	246	.0000184	.0125	675
Petrified Forest, Arizona	.160	19	119	.00125	.338	270
	.149	19	127	.00109	.274	254
	.104	11	106	.0053	.184	253

Three basins were measured from a special map of badland topography on the Chinle formation in the Petrified Forest National Monument, Arizona. This area was mapped during the summer of 1949 by Mr. Brainerd Mears, Jr., of Columbia University. The scale of the map is 1/480; the contour interval five feet. The region has a semi-arid climate in which summer rains are sporadic and torrential. The weak nature of the Chinle formation and the lack of a vegetal cover result in the formation of a finely-dissected badland topography. Values for the texture ratio in the three basins measured were all slightly greater than 100, as shown in table 3.

These results indicate that the texture ratio for badlands can greatly exceed the values established in this paper for fine-textured topography. However, when the usual United States Geological Survey or Army Map Service topographic map is used, with a scale of 1/24,000 or smaller, any area having a texture ratio greater than 10.0 will appear as finely dissected as the limitations of the map scale will permit. Increasing drainage densities are not further differentiated beyond this point by the contour map.

The term "ultra-fine texture" may be applied to areas having a texture ratio greater than 50. Texture ratios of this magnitude are adequately shown only on large scale and detailed maps such as those of the Perth Amboy clay topography and the Chinle badlands.

RELATION OF TEXTURE RATIO TO DRAINAGE DENSITY

A comparative study has been made of the relation between the texture ratio ($T=N/P$) and Horton's drainage density ratio ($D_d=\Sigma L/A$). In order to establish this relationship, drainage lines were drawn into each channel indicated by the contours so that the total lengths could be measured. Using these data it was possible to determine the drainage density for the fifty-four basins for which the texture ratio had been determined.

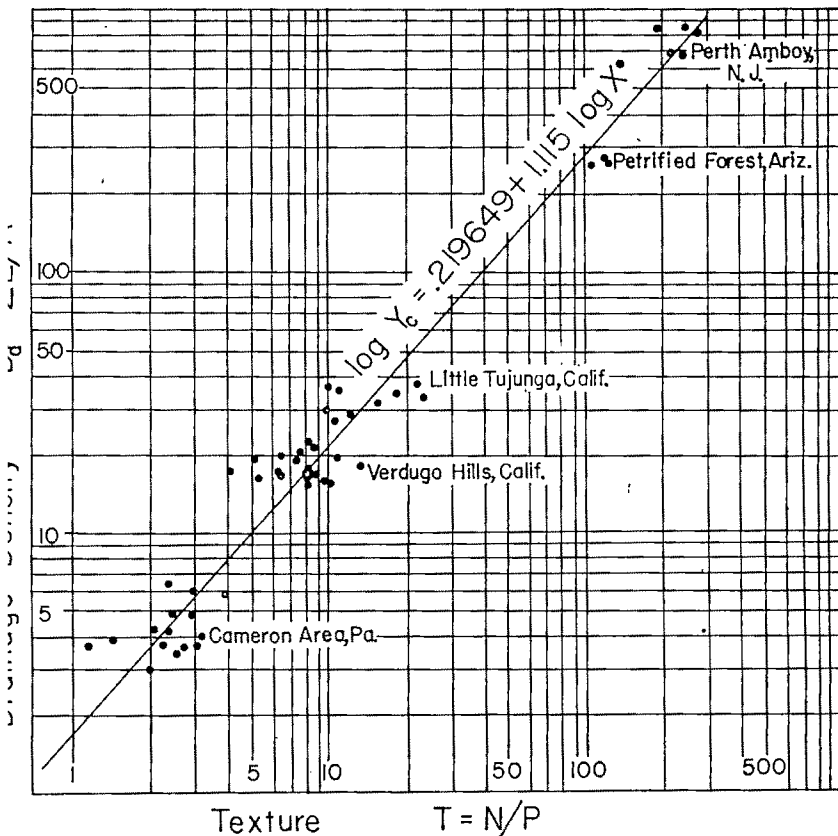


Figure 6. Relation of the texture ratio to drainage density.

The data were then plotted on log-log paper; the values for drainage density as ordinates, texture ratios as abscissas (fig. 6). The points formed a scatter zone approximating a straight line, indicating that the drainage density is a logarithmic function of the texture ratio. An estimating equation was then derived using the general form:

$$\log Y_c = \log a + b \log X$$

which is the logarithmic form of:

$$Y_c = a X^b.$$

By the method of least squares the following constants were derived:

$$\log a = .219649$$

$$b = 1.115$$

Substituting these values in the general equation we have:

$$\log Y_c = .219649 + 1.115 \log X.$$

Using figure 6, it is possible to translate any value of texture ratio into the approximate equivalent drainage density, or vice versa. The latter procedure is of value when one has only an air photograph, from which only drainage density can be measured and the equivalent texture grade is desired. The high degree of correlation in the two sets of values serves as a check upon the over-all consistency of the texture ratio method as a simple means of grading texture from contour topographic maps.

In conclusion it is hoped that these standards for grading texture from contour topographic maps will prove of value in later quantitative geomorphic studies in which causative factors are being related to land forms.

Acknowledgment is made to Professor A. N. Strahler, of Columbia University, who suggested the study and supervised the research.

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COLUMBIA UNIVERSITY,
NEW YORK, N. Y.

COMMUNICATION

NEW JOURNAL OF INTEREST TO GEOLOGISTS

A new geochemical journal, *GEOCHEMICA ET COSMOCHIMICA ACTA*, is being published by Butterworth-Springer, 436 Strand, London, W. C. 2, England, under the editorship of Professor L. R. Wager. The journal is international in scope and the plan is to give prompt publication to geochemical papers from all over the world. They will be published in English, French or German, with English summaries. Authors are to be given 75 reprints free of charge. Manuscripts should be sent to Earl Ingerson, U. S. Geological Survey, Washington 25, D. C., who is American editor for the new publication.

Subscription prices have not yet been announced, but the American agent is the Academic Press, Inc., 125 East 28rd Street, New York 10, New York, to whom inquiries should be addressed.

REVIEWS

The Geology of the Bergamasc Alps, Lombardia, Italy; by L. U. DE SITTER and C. M. DE SITTER-KOOMANS. 257 pp., 88 text figs., 48 plates. Overdruk uit Leidse Geologische Mededelingen, Deel XIV-B, 1949.—This substantial contribution to knowledge of geology in the southern part of the Alps is the result of summer field studies, in the years 1926 to 1939, by staff members and advanced students of Leyden University. The area mapped in detail has a maximum length of about 52 miles, extending from Lake Como on the west to the Oglio River on the east; it varies in width from 12 to 25 miles, the northern boundary lying near parallel of latitude $46^{\circ} 05'$. Bedrock geology of this area is depicted on two attractive sheets, in colors, to the scale 1:50,000, with topographic contours spaced at 100 meters. Two additional sheets, also in color, show to the same scale 27 structure sections, all extending north-south, essentially at right angles to the structural grain. Four additional folded plates, drawn to smaller scales, show (1) igneous bodies of the Bergamasc Alps; (2) major tectonic features of the area, by line symbols and by generalized structure contours; (3) tectonic features of a much larger area, the entire Lombardic Alps; and (4) variations in thickness and facies of the sedimentary formations, in a generalized west-east section from the Lugano region to South Tyrol.

The textual treatment is divided into three principal sections. Part I deals with the petrography of metamorphic and igneous rocks, and includes numerous chemical analyses. These rocks con-

sist of: (1) the "basement series" of ortho- and paragneisses, injection gneiss, phyllite, amphibolite, and other metamorphic types, all cut by bodies of granitic rocks, chiefly granodiorite, believed to be of late Carboniferous (Asturian) age; (2) Permian volcanic rocks; (3) Triassic and Tertiary intrusive bodies.

Part II describes the sedimentary formations which, exclusive of Pleistocene and Recent deposits, range in age from Permian through the three Mesozoic periods. The total thickness of pre-Cretaceous systems reaches a maximum of more than 20,000 feet in the central part of the area. There are striking similarities, at a number of horizons, to sections displayed in the East Alpine thrust sheets of Austria. This part of the monograph presents much information of value to students of lithofacies, and also to biostratigraphers.

Part III describes the structure and outlines the tectonic development of the Bergamasc mountain unit. In this division of the Alps the thrusting and overfolding are directed in the main toward the south, in contrast to the northward-reaching nappes of Switzerland. The Insubrian Line, marking a sharp boundary between the two unlike structural provinces, extends nearly east-west some miles north of the Bergamasc Alps. Directly north of the line the thrust sheets of the Central Alps are essentially vertical; this is the "root zone" of the Pennine nappes. South of the line is the Orobic belt of basement rocks, which has been thrust southward to form the highest structural "tread" of the Lombardic Alps. Other thrusts and related folds, affecting the sedimentary section, complete a series of broad steps descending to the Po River plain. The structure is locally complex, but as a whole is much simpler than that of the Swiss Alps. From the Insubrian Line southward the deformation represents the later (post-Oligocene) Tertiary episodes of Alpine orogeny.

We are indebted to our Dutch colleagues for a clear presentation of their results in English. Although numerous words are misspelled, there is no difficulty in following the exposition. How many geologists of the English-speaking world could so successfully write a similar monograph in Dutch, or in any other language of the European continent?

CHESTER R. LONGWELL

Allgemeine Botanik—Ein Lehrbuch auf vergleichend-biologischer Grundlage; by WILHELM TROLL. Pp. xv, 749. Stuttgart, Germany, 1948 (Ferdinand Enke Verlag, DM 56.00, 60.00 bound).—This new and voluminous text is an original attempt to provide a much needed modern treatment of general botany covering a considerable diversity of subjects, namely morphology, anatomy (including cytology and histology), physiology (including nutrition, respira-

tion, water relationships, morphogenesis and tropisms), and reproduction, but excluding genetics. As a fundamental text the book is significantly unorthodox and differs from other older standard works both in the selection and the arrangement of its subject matter.

Morphology and discussions of morphological principles form the backbone of the book, but some aspects of physiology are also very adequately treated and numerous biochemical data not usually given in this kind of general text have been included. Theoretical considerations manifest a good understanding of the evocator-reaction system concept and of the plant as a self-regulatory entity. In addition, useful parallels are drawn between plants and animals. Some aspects of growth and differentiation, now prominent in contemporary research, have been treated relatively briefly or are omitted, such as growth-relationships, meristems, synthetic growth substances, and the concepts of reactivity, potency and determination.

Led by holistic-morphological principles, the author has abandoned in his text to a considerable degree the customary segregation of physiological and morphological topics. Thus osmosis, turgor, etc., are treated under the heading of cytology while some anatomical and morphological features appear in the physiological sections. The ensuing diffusion of the subject matter is, however, somewhat counteracted by good cross-reference from one chapter to another. Didactically this may be subject to some criticism, as may the introduction of certain terms, such as *Ueberpflanzen* (superplants) for epiphytes, which seem unnecessary and impractical. These, however, are minor considerations affecting little the usefulness of this interesting book which contains a profusion of good illustrations. More serious is the omission of citations, a bibliography, and an author's index.

ROBERT BLOCH

Giant Brains or Machines That Think; by EDMUND C. BERKELEY. Pp. xvi, 270. New York, 1949 (John Wiley & Sons, Inc., \$4.00).—Complex machinery for handling information and computing is, every day, attaining a position of greater importance in modern technology. In this provocative volume Mr. Berkeley describes the mechanical structure and operation of some of these machines and attempts to evaluate their present and future significance to society. The author, who has a wide background of experience in the field of automatic computing machinery, is well qualified for the task he has undertaken.

Giant Brains begins with a discussion of the sense in which machines may be said to be capable of thinking. It illustrates some of the types of mechanical thought with reference to a specific simple

mechanical brain, which the author calls Simon after a distinguished predecessor. Simon, however, is not as simple as the reader may at first hope. If actually constructed, he would require approximately fifty relays connected in a very formidable electrical network.

Punched-card calculating techniques, which play an important role in many modern mathematical computers and which are used, as well, in business and accounting, are treated in detail. Separate chapters are reserved for discussions of the components, capabilities and operational procedures of four representative calculators in use at the present time. These are the Massachusetts Institute of Technology's Differential Analyzer No. 2, the IBM Automatic Sequence-Controlled Calculator at Harvard, the ENIAC (Electronic Numerical Integrator and Calculator) developed at the University of Pennsylvania, and the Bell Laboratories' General Purpose Relay Calculator.

A recent machine of a different sort, the Kalin-Burkhart Logical Truth Calculator, which solves problems in Boolean algebra (the algebra of logic), is explained. This fascinating computer promises to be useful in drafting complex contracts and in checking them for freedom from "loop holes" and logical contradictions.

Mr. Berkeley, in the final chapters, discusses the Giant Brains of the future and the dangers which they may present to society. He concludes that the chief perils are the physical harm which robot-controlled weapons can inflict and the unemployment which combinations of thinking and acting machines may produce by usurping the functions of men. The real and immediate necessity for serious thought on these problems is forcefully argued.

The author is careful to explain in the preface that the book has been written with the use of a minimum of technical terms and concepts. It is, he says, intended for everyone. Unfortunately, this quest for universal appeal and understanding makes the work, in many instances, superficial. The reader's interest is often aroused to a high peak by a provocative statement; but the subsequent explanation is frequently so shallow as to leave him rather unsatisfied.

A very valuable bibliography of more than 250 references on calculators and related topics is included in *Giant Brains*. This would serve as an excellent starting point for a deeper investigation of the field.

FRANKLIN C. BROOKS

American Journal of Science

OCTOBER 1950

EQUILIBRIUM THEORY OF EROSIONAL SLOPES APPROACHED BY FREQUENCY DISTRIBUTION ANALYSIS

ARTHUR N. STRAHLER

PART I

ABSTRACT. In the quantitative analysis of erosional landforms one of several form-elements requiring measurement is slope angle of valley walls. Field sampling of slope angles in several mature regions differing widely in lithology, relief, vegetation, climate and soils has yielded data suited to frequency distribution analysis. Determination of means, estimated standard deviations, skewness and normal distribution fitness have provided a quantitative basis for slope description and significance tests.

Distributions show a wide range of means, but are symmetrical and have low dispersions. This is taken as evidence of a prevailing condition of form-equilibrium accompanying a steady state in an open system of erosion and transportation. Comparison of valley-wall slopes with adjacent channel gradients reveals a strong, positive correlation, indicating a high degree of adjustment among component parts of a drainage system.

Tests for significance of differences in slope means of three localities in the Verdugo and San Rafael Hills showed that (1) factors other than lithology exert major control over observed differences in slope angles, (2) directional exposure has no significant effect upon slope angles, and (3) slopes left to weathering, sheet wash and creep without stream corrasion at the base have reclined in angle.

INTRODUCTION

A LARGE proportion of the earth's land surface is composed of erosional landforms produced by channel erosion in drainage networks operating in conjunction with raindrop and sheet-runoff erosion and mass gravity wasting on the contributing slopes. In a mature stage of development the landscape consists of an intricate combination of channels, slopes and divides. Although the same unit form is not exactly repeated throughout this type of topography, an observer cannot fail to recognize that the forms are approximately the same throughout an area having a uniform lithology, geologic history, climate, soil and vegetation. Examples may be cited from

the intricately dissected California Coast Ranges; from the monotonously repetitious landforms of the dissected Appalachian Plateaus; or from the marl hills of badlands in northern Arizona.

Although our understanding of erosional landforms is still in a stage of generalized verbal description, some attempts have been made to separate the various elements of form from the topographic complex. Robert E. Horton (1945) has analyzed drainage network composition in terms of drainage density, stream frequency, stream number, stream order, and bifurcation and length ratio.

Despite the apparent complexity of a quantitative analysis, it is possible to define and measure the various form-elements which comprise a fluviially dissected landscape. This is the first step in an over-all investigation aimed at relating quantitatively the influence of causative factors to form characteristics. Slope is one of the form-elements and is the principal topic of this paper.

In considering quantitatively the element of slope in an erosional landmass it is possible to measure and compare (1) forms of slope profiles as mathematical curves, (2) lengths of slopes from divide to base (scale-aspect of the topography), and (3) angles of slope with respect to the horizontal (gradient-aspect of the topography). Because the principal concern of this paper is with the third measure, the first two are discussed only briefly.

In a maturely dissected region of homogeneous rock the common slope profile, when taken along an orthogonal line with respect to the contours, tends to be straight in its middle and lower parts (fig. 1). At the upper end the profile becomes convex-up, passing into the rounded divide. Where streams are effectively corradng a channel at the slope base the profile continues to the base as a nearly straight line (plate 1). Concavity at the base, so commonly shown in elementary textbooks, seems to occur only where accumulations of slope-wash or slide-rock lie at the slope base, or where structural control is present. Straightness of profile has been noted by Lawson (1933) in the California Coast Ranges and by the writer in that same province as well as in many other places in the United States. It may be seen in the bold mountains of the Great Smoky mass as well as in small-scale badland forms in

weak clays. The common illusion of generally concave-up slopes comes from viewing profiles of lateral spurs or other lines which are not true orthogonals.

Length of slope, a function of the general scale of the drainage network, is related to the infiltration capacity and resistivity of the surface to corrasion and other factors and is therefore left to be treated elsewhere in quantitative considerations of drainage density and its variations.

Slope steepness is a particular form-element which lends itself to analysis by the standard methods of frequency distribution statistics. Even the most casual geological observer has noted that slope steepness varies widely from one region to another, but that it seems fairly constant within the limits of a small area of uniform relief and rock composition. Thus slopes may be said to reflect a steady state in the rate of removal of debris and the rate of supply of debris. Slopes seem to tend toward a constant angle which is related to the particular conditions of

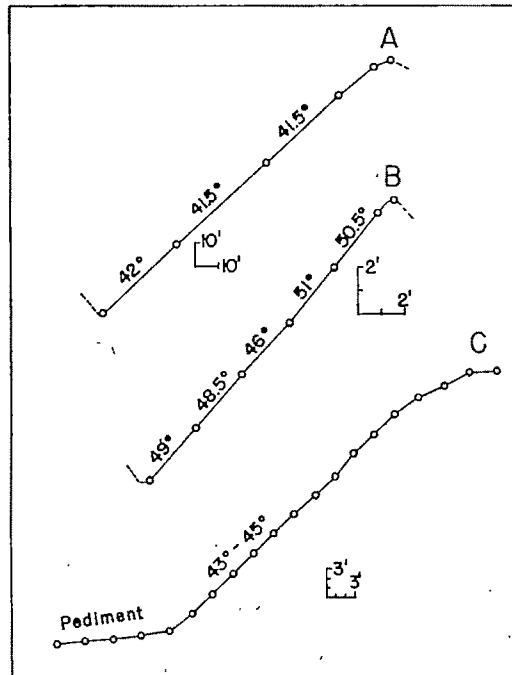


Fig. 1. Profiles of three valley-wall slopes surveyed in the field. (A) Verdugo Hills, Los Angeles Co., California. (B) Dissected clay dump, Perth Amboy, N. J. (C) Petrified Forest National Monument, Ariz.

soil, bedrock, vegetation, climate and relief, and which is integrally adjusted with conditions of channel gradient and stream regimen.

The concept of equilibrium has long been applied to graded streams and their associated slopes but the nature of this equilibrium and its basic similarities with other systems of equilibrium in nature seem not to have been fully examined. A graded drainage system is perhaps best described as an open system in a steady state (von Bertalanffy, 1950) which differs from a closed system in equilibrium in that the open system has import and export of components. An example of an open system in physics might be the flow of heat through a conducting solid. When a steady state is attained the temperature at a given point remains constant while the flow of heat continues. In biology the metabolism of a stable organism is best described as operating in a steady state requiring an exchange of materials with the environment and a continuous building up and breaking down of materials within the organism. Open systems consume energy to maintain a steady state, whereas closed systems require no energy for the maintenance of equilibrium. Still another property of the open system is that a disturbance in the flow of materials or energy will cause a readjustment to take place until a time-independent steady state is reestablished.

In a graded drainage system the steady state manifests itself in the development of certain topographic form characteristics which achieve a time-independent condition. (The forms may be described as "equilibrium forms".) Erosional and transportational processes meanwhile produce a steady flow (averaged over periods of years or tens of years) of water and waste from and through the landform system. Potential energy of position is transformed into kinetic energy of water and debris movement or heat. Over the long span of the erosion cycle continual readjustment of the components in the steady state is required as relief lowers and available energy diminishes. The forms will likewise show a slow evolution.

Applied to erosion processes and forms, the concept of the steady state in an open system focuses attention upon the relationships between dynamics and morphology. With this concept in mind, the first steps in measurement and description of slope forms typical of the steady state can be undertaken.

ACKNOWLEDGMENTS

The writer wishes to thank Dr. Howard Levene of the Department of Mathematical Statistics, Columbia University, for critically reading the paper and suggesting improvements. Field work in 1947 was supported by the Kemp Memorial Fund of Columbia University and in 1948 and 1949 by Grant 525-48 from the Penrose Bequest of the Geological Society of America.

GENERAL PRINCIPLES

Method of Obtaining Field Data.—Slope sampling requires decision as to (1) type of data wanted, (2) rules of sampling to be followed in the field, and (3) size of sample required.

In the present investigation it was required that only the steepest part of a profile line of slope be measured; furthermore, that the profile line must follow the true down-slope line from divide to base of slope (the orthogonal line with respect to contours). Following this rule the observer is prevented from having a choice as to what part of a profile to select; the use of apparent, rather than true maximum slopes is avoided. Thus any two or more observers should obtain the same angle of slope from any given point in the field, subject only to errors of measurement.

There is a more important and fundamental reason for using the steepest part of a slope profile. It is postulated that in mature topography a slope is the morphological manifestation of a steady state in which the forces which remove material are so adjusted to the resistive properties of the surface as to provide a steady supply of debris to the streams. The steepest part of a slope will then reflect the maximum angle which can be maintained, and is an indicator of the relative effectiveness of the opposed forces in the equilibrium relationship. Because the slope at its upper part declines in angle to become horizontal on the divide, angles less than the maximum have little significance and their use would bring in a broad element of subjective sampling. As the ultimate aim in geomorphology must be a dynamic understanding, it is essential that those form-elements be measured which can be most easily related to causative forces.

In field sampling, only valley-wall slopes leading down into the sides of a channel were used. Slopes leading into the ex-

treme head of a ravine were not used because of the element of strong convergence present. Slopes down the axes of spurs, where lateral divides descend to a main stream, were not used because these are not true orthogonals. Drainage basins of the first and second, sometimes third orders were used. Avoidance of higher order master streams eliminates the reading of slopes abnormally steepened by strong lateral corrasion of a large stream.

Within each area an attempt was made to take slope readings at approximately equally spaced positions along the contour. In the case of fine-textured badlands these were spaced only 5 to 10 feet apart, or about one-fourth to one-half of the prevailing slope length. In medium-textured topography with slope lengths of 100 to 300 feet the spacing was 100 to 150 feet. This raises the question of how close together any two profile lines can lie before they can be considered as one statistical item in a frequency distribution, rather than as two separate items. The problem exists because the sampling is from a continuous surface which varies in orientation from place to place, rather than from a population of discrete pieces or objects, as for example, a clastic sediment. Because all movement of detritus on a slope takes place along the true down-slope profile lines, one would not have to move far laterally along a slope to encounter relatively independent threads of debris movement. With the spacing used by the writer successive profiles were separated by what seemed to be a relatively broad belt of slope, equivalent to one-half to one-third of the slope length itself; hence no mutual interference seemed likely.

Slope angles were read to the nearest degree or half degree with Abney hand level or Brunton compass. A class interval of 2° or more is desirable in the frequency distribution analysis, because the range of error for any item is almost a half degree. On mountain or hill slopes the steepest down-slope line was determined by rolling boulders or pebbles down-slope, or by selecting the maximum of a range of readings aimed down-slope through a lateral arc. When a two-man team is used, each man takes a position on the slope line. The instrument man then reads the slope to the eye-level of his partner. In this way minor ground irregularities and brush can be overcome. When one is working alone, he can put up a perpendicular rod with the eye-level marked, or make a mark at eye-level on a

convenient tree trunk or bush. Slopes were read over lengths equivalent to one-fourth or one-fifth of the slope length so as to avoid minor irregularities made by boulders or clumps of vegetation. As most slopes are relatively straight or steepen toward the base the measurement is taken near the base. Some slopes have a basal concavity due to local accumulations of slopewash or talus; the slope is then read above the zone of accumulation. In the case of small-scale badlands a 3-foot board was laid on the slope and the measurement taken as with dip of a bedding plane.

It is desirable to read the azimuth of each slope measurement so as to permit study of the effects of direction of exposure on slope angle. Readings should be located on the field map by a station number corresponding to the notebook record. This permits statistical analysis between individual basins or groups of basins.

Sample sizes taken by the writer ranged from 20 to 200 readings. Subsequent statistical analysis has shown that a sample of 50 slopes is adequate to reveal the characteristics of the distribution in a homogeneous region of 6 to 12 first-order drainage basins; while a sample of 25 will closely fix the mean.

The use of topographic maps as sources of slope data has been investigated and tests run between field and map readings of the same slopes. The statistical analysis of this procedure is treated in a later section of this paper. Regarding collection of data from maps the following conclusions have been reached: Maps on a scale of 1:24,000 or 1:25,000 published by the U. S. Geological Survey and the Army Map Service in recent years will give reasonably accurate results where topography is coarse-textured and the relief strong. These maps are prepared by photogrammetric methods and comply with National Standard map accuracy requirements. It was found that maps of a scale of 1:31,680 in Los Angeles County are unsuited to slope sampling because the topographic texture is too fine for the map scale and contour interval; i.e., slopes are too short to be represented accurately under the cartographic conditions. Maps of the scale 1:62,500 are generally beyond the limits of reasonable accuracy and should be entirely avoided for slope sampling.

General Characteristics of Slope Frequency Distributions.—The methods of slope sampling described above were applied

to several areas differing widely in lithology, soil, relief, vegetation, and climate in order to obtain some idea of the range of characteristics present and the degree of homogeneity within each area. Figure 2 shows several histograms drawn on a common abscissa to show comparative positions on the slope scale 0° to 90°. For each distribution the following measures are given:

N Number of items in the sample.

$\bar{X}$ Arithmetic mean.

s Estimated standard deviation.

Cumulative frequency percentage distributions for the same samples are shown in figure 3. Both step-graphs, showing individual classes, and smoothed curves are shown.

With regard to general distribution properties, two points are especially noteworthy: (1) Dispersions are low, considering the range of angle possible, giving evidence of a high degree of homogeneity in the populations sampled. (2) Distributions are generally symmetrical, the principal exception being sample D. Inasmuch as sampling was carried out according to previously set rules and no readings were discarded

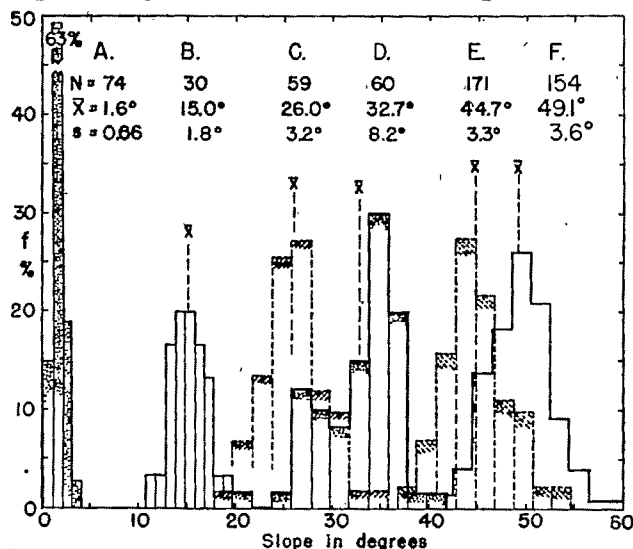


Fig. 2. Histograms of six slope frequency distributions. (A) Steenvoorde, France, (B) Rose Well gravels, Arizona, (C) Bernalillo, N. M., Santa Fe formation, (D) Hunter-Shandaken area, Catskill Mts., N. Y., (E) Kline Canyon area, Verdugo Hills, Calif., (F) Dissected clay fill, Perth Amboy, N. J. All data except (A) from field readings.

arbitrarily, either during the field sampling or during the processing of the data, the low dispersions and symmetry are interpreted as an indication that within a given small region where conditions of lithology, climate, soil, vegetation and relief are uniform, slopes tend to approach a certain equilibrium angle, appropriate to those controlling factors.

Slope Distributions and the Normal Curve of Error.—The problem of whether the distribution of maximum slopes in a selected region follows the normal curve of error was considered worthy of analysis in view of the possibility that the distribution is inherently skewed and is better represented by a logarithmic-normal curve, or some other variety of normal curve, such as one in which the abscissa is on a scale of tangents or log-tangents.

Three methods were used in analyzing the form of the distributions: (1) A plot on arithmetic probability paper. (2) A fitted normal curve and χ^2 test of goodness of fit. (3) Determination of significant skewness and kurtosis based on the third and fourth moments of the distribution.

A rough test of normal distribution may be had by plotting cumulative percentage frequencies on arithmetic probability paper. This paper is constructed to show the normal curve of

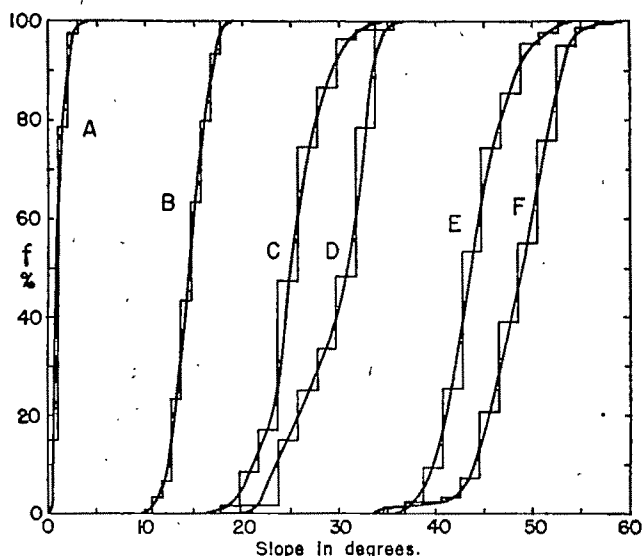


Fig. 3. Cumulative percentage frequency distributions. Same data as in figure 2.

error (cumulative) as a straight line. If the distribution appears reasonably straight one can proceed to fit a normal curve to the data. An additional feature of the cumulative curve on probability paper is that the slope is proportional to dispersion, hence the differences in dispersions between two normal distributions can be noted at a glance.

Figure 4 shows the data of figure 3 plotted on arithmetic probability paper. End classes containing only one item have been combined to compensate for the influence of scarcity. With the exception of sample D and the lower tail of sample F a reasonable straightness prevails, suggesting that the distributions are well described by normal curves, which may now be fitted to the data.

Fitting of the normal curve to the slope data of sample C, an area of dissected Santa Fe formation near Bernalillo, New Mexico, is illustrated in figure 5.

Goodness of fit has been determined by use of a χ^2 test in which theoretical frequencies and observed frequencies are compared as follows: (Croxtton and Cowden, 1946, p. 286)

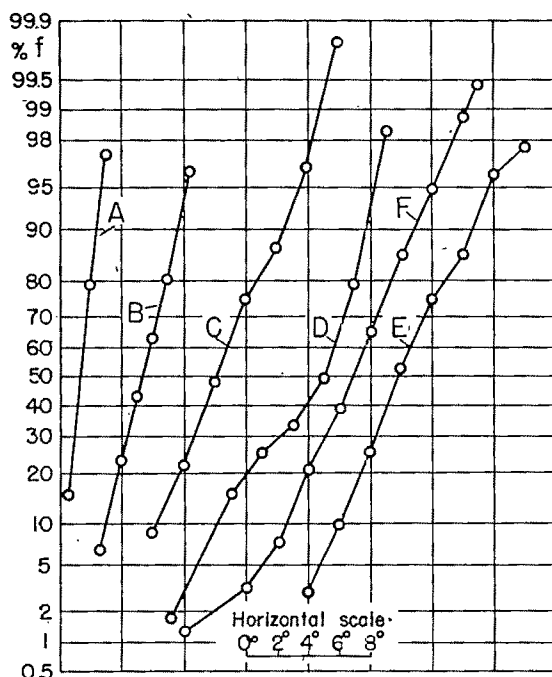


Fig. 4. Cumulative percentage frequency distributions on arithmetic probability paper. Same data as figures 2 and 3.

$$\chi^2 = \sum \frac{(f - f_o)^2}{f_o} = 0.631 \quad \text{where}$$

f = observed frequency
 f_o = expected frequency

The value n , representing the number of degrees of freedom, is obtained by subtracting the three degrees of freedom lost in the curve-fitting process from the original number of classes, seven, and is therefore equal to four. By consulting a prepared table we find for these values of χ^2 and n a probability, P , of approximately 0.97. Thus a normal curve of error is an excellent description of the distribution and, if the distribution is in fact normal, we should expect to find this good a fit or better in only 6 times out of one hundred such samples because of chance variations due to sampling only.

Tests of significant skewness and kurtosis were carried out on the raw data of three frequency distributions of slopes in the Verdugo and San Rafael Hills, Los Angeles County, California¹.

The purpose of the investigation was to determine if the various amounts of skewness and kurtosis visible in the three distributions are of such an order as to be commonly ob-

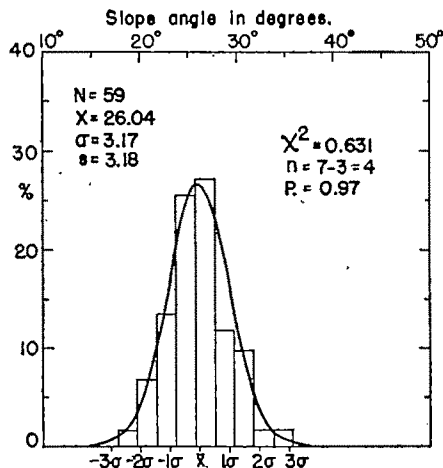


Fig. 5. Normal curve of error fitted to a frequency distribution of slope angles from the dissected Santa Fe formation near Bernalillo, New Mexico. Slopes measured in field.

¹The analysis was carried out under the direction of Mr. Richard Ostheimer, Instructor in Statistics, Columbia University. Moments were computed from the raw data in order to remove possible influences of grouping.

tained by chance variations in sampling of a normal population, or whether they are significant of actual departures from normal in the population (fig. 6).

Skewness was determined from the value of β_1 , a measure of skewness based upon the third moment of the frequency distribution:

$$\beta_1 = \frac{N (\sum x^3)^2}{(\sum x^2)^3}$$

Table 1 shows the results and conclusions for samples A, B, and C of figure 6. Samples B and C showed no significant skewness; sample A is doubtful of interpretation. Kurtosis was determined by the value of β_2 , a measure of kurtosis based upon the fourth moment of the frequency distribution:

$$\beta_2 = \frac{N \sum x^4}{(\sum x^2)^2}$$

TABLE 1

Summary of analysis of skewness in three sample slope frequency distributions.

DETERMINATIONS MADE	Area A	Area B	Area C
β_1 (Distribution symmetrical when β_1 is 0; Right skewness when β_1 is +; left skewness when β_1 is -)	+0.153	-0.005	-0.103
Probability of sample β_1 at least this large, if β_1 of universe is 0.	0.02 to 0.10	>0.10	>0.10
g_1 (Normally distributed measure of skewness. Symmetry when $g_1=0$.)	0.394	0.070	0.340
$\frac{g_1}{\sigma_{g_1}} \left(\frac{x}{\sigma} \right)$ of a normal curve)	2.12	0.27	0.75
Probability of sample g_1 at least this large if g_1 of universe is 0.	0.02	0.39	0.23
Is the skewness significant?	?	No	No

Table 2 shows the results and conclusions for samples A, B and C. None of the samples shows significant kurtosis although the probability shows a considerable range.

The general conclusion which may be stated from the analysis of β_1 and β_2 is as follows: There is no reason to doubt that frequencies of each of the three areas are normally distributed. A possible exception is area A, in which the sample has right skewness, but the skewness is of questionable significance.

Law of Constancy of Slopes.—The tendency of slopes to group closely about a mean value may be taken as an expression of a morphologic law relating slope to other form factors. This

law may be stated as follows: Within an area of essentially uniform lithology, soils, vegetation, climate and stage of development, maximum slope angles tend to be normally distributed with low dispersion about a mean value determined by the combined factors of drainage density, relief and slope-profile curvature.

TABLE 2
Summary of analysis of kurtosis in three
sample slope frequency distributions.

DETERMINATIONS MADE	Area A	Area B	Area C
β_1 (Distribution normal, mesokurtic, when $\beta_1=3.0$. Leptokurtic, or peaked, when $\beta_1 > 3$. Platykurtic, or flattened, when $\beta_1 < 3$.)	2.992	3.707	2.381
Probability of sample β_1 differing by at least this much from a population β_1 of 3.0	0.05	0.05	0.05
g_2 (Normally distributed measure of kurtosis. Mesokurtic when $g_2=0$.)	0.027	0.819	0.485
$\frac{g_2}{\sigma_{g_2}} \left(\frac{x}{\sigma} \text{ of a normal curve} \right)$	0.07	1.62	0.55
Probability of sample g_2 at least this large, if g_2 of universe is 0.	0.47	0.05	0.29
Is there significant departure from normal, mesokurtic form?	No	No	No

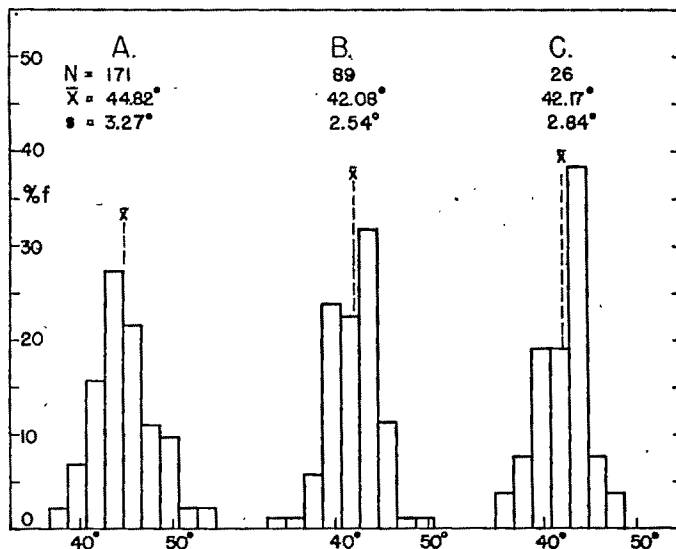


Fig. 6. Histograms of three slope frequency distributions from the Verdugo and San Rafael Hills, California. Location of areas A, B, and C is shown in figure 10. See tables 1, 2, 3, 4, 5, and 6 for summaries of data analysis.

If drainage density (Horton, 1945, p. 248),

$$D_d = \frac{\Sigma L}{A} \quad \text{where } \Sigma L = \text{sum of stream lengths} \\ \text{(projected onto a horizontal plane)} \\ A = \text{area.}$$

then the mean horizontal distance from divide to channel is roughly one-half of the reciprocal of drainage density:

$$H = \frac{1}{2D_d} \quad \text{where } H = \text{horizontal distance from stream to divide.}$$

Now, if the spacing of streams is uniform throughout and the length of contributing slopes is similarly uniform, slope steepness can vary only as relief or profile curvature are varied (fig. 7).

Given two areas of the same drainage density, the area having the lower relief must have lower slopes, assuming profile curvature characteristics to be similar (fig. 7A). Given two areas of similar relief, but of different drainage density, slope must be less steep where drainage density is less (fig. 7B). If divides are broadly convex and only the basal fraction of the slope is straight, a steeper maximum angle is required than in a region of narrow divides and long, straight slopes, even though relief and drainage density are the same in both areas (fig. 7C). Because divide curvature is a factor readily influenced by stage of development or by structural conditions, it can be minimized only by the use of mature areas which behave as if lithology and structure were homogeneous.

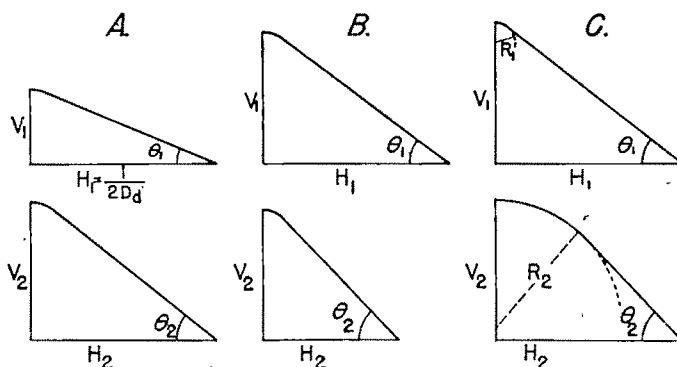


Fig. 7. Relationship of relief (V), slope (θ) and horizontal distance between divide and stream (H). Radius of divide curvature, R , is a variable diagram C .

Slope is thus seen to be proportional to the ratio between relief and one-half of the reciprocal of drainage density, assuming constant profile curvature characteristics. From figure 1 it is apparent that profiles are similar in form for both the fine-textured badlands on dissected clay fill near Perth Amboy (A) and for the medium-textured Verdugo Hills in Los Angeles County (B). Both have long, straight slopes and only a small curvature radius at the divides (plates 1 and 2). On the basis of detailed profile plotting of slopes in the field and plane table mapping it appears that relief in the first area is about 20 times the second, but drainage density is only 1/20 as great, so that the slope angles are of the same general order of magnitude (fig. 2, E, F). If land slopes were perfectly straight from divide to base, the relationship of relief to drainage density would be approximately

$$\tan \theta = \frac{\frac{V}{1}}{2D_d} = 2VD_d \text{ where } \theta = \text{slope angle}$$

$V = \text{relief (average vertical distance between divide and channel)}$

$D_d = \text{drainage density}$

For example, it was found in the Perth Amboy locality that the mean of a large number of measurements of vertical distance between channel and divide was approximately 6.0 feet, or 0.00114 miles. Drainage density sampled from several basins was 500 (that is, 500 miles of channel per square mile of area, projected upon a horizontal plane). Then

$$\tan \theta = \frac{\frac{V}{1}}{2D_d} = \frac{0.00114}{0.00100} = 1.14$$

$\text{and } \theta = 48.7^\circ$

Note that the mean of slope readings in this area as shown in figure 2, sample F, was 49.1°. One would not normally expect such good agreement between calculated and observed slope angles, and because the range of error has not been investigated, the coincidence may be misleading.

Relations of Slopes to Channel Gradients.—Davis (1909, p. 266-268) clearly stated the concept that the slopes of a mature landmass are graded, as are the streams. We may restate this principle by saying that slope profiles are in equilibrium with the channel profiles to which the slopes contribute their debris.

For a given area free of systematic structural control, but subject to uniformly controlling factors of climate, vegetation, soil and stage of development, all morphological characteristics tend to approach a time-independent form. Ground and channel gradients, as well as drainage density achieve a form best adapted to maintaining a steady state in the removal of debris. This is simply an extension of Playfair's Law to include all form-aspects of the topography.

If the type of adjustment described above actually exists, one would expect the angle of slope of valley walls to vary systematically with gradient of channel at the slope base. Steep ground slopes would be expected to correspond with steep channel gradients; low ground slopes with low stream channel gradients. This relationship has been stated by R. E. Horton (1945, p. 285) who uses the definition

$$\text{slope ratio} = \frac{S_c}{S_g} \text{ where } S_c = \text{channel slope} \\ \text{and } S_g = \text{ground slope}$$

Ground slope can be determined by the field methods previously described in this paper. For each slope reading the channel gradient at the base of the slope would need to be measured. This was not done in the field by the writer, but the general trend of the slope ratio was obtained from large-scale topographic maps, including two which were specially mapped for the present study. Figure 8 shows the means of ground slopes and channel slopes plotted on log-log paper. Each point represents means of a large number of measurements of ground slopes and channel slopes. Because samples were taken from maps and the correlation is believed to have wide inherent spread of values, a curve was fitted by inspection. We might say that, if these data are representative of general conditions, ground slope varies as somewhat less than the first power of channel slope, and that the slope ratio tends to range from 1/5 or 1/4 for low values of slopes, up to about 1/2 in the higher values.

There are several uncertain elements in the foregoing analysis. Data from a greater number of regions would be expected to modify the estimating equation considerably. Substitution of careful field measurements for map measurements would increase the confidence in the data. It is further obvious that channel slope steepens rapidly toward the head of a valley, whereas ground slope tends to remain nearly constant along the



Plate 1. Topography of Verdugo Hills. Cabrini Canyon, south side of Verdugo Hills, Los Angeles Co., Calif. Slope in foreground faces northwest, had chamise-chaparral cover prior to burning. Canyon is about 200 feet deep.



Plate 2. Topography of Perth Amboy badlands. Badlands in clay-sand backfill, Perth Amboy, N. J. Relief in this photograph is 20 to 80 feet. This topography is similar in form-characteristics to that shown in plate 1.

sides of the valley, as the frequency distribution studies show. To minimize this variable, which can easily vitiate the results, readings were made along second-order stream basins, near the point where they are formed by the junction of two first-order streams (Horton, 1945, p. 281). This assures that all data come from the same relative position in the drainage system. Further standardization is desirable.

There is a suggestion from the data of figure 8 that climate has a profound influence on the slope ratio. Areas 7 and 9, which lie to the right of the line of the estimating equation, and area 8 which is on the line, have typical bare ground surfaces of badlands, or are lightly covered by chaparral, as in the Mt. Gleason area (7). Here one might expect a given slope of valley side to supply proportionately more detritus to the channel than a comparable slope in vegetation-clothed regions

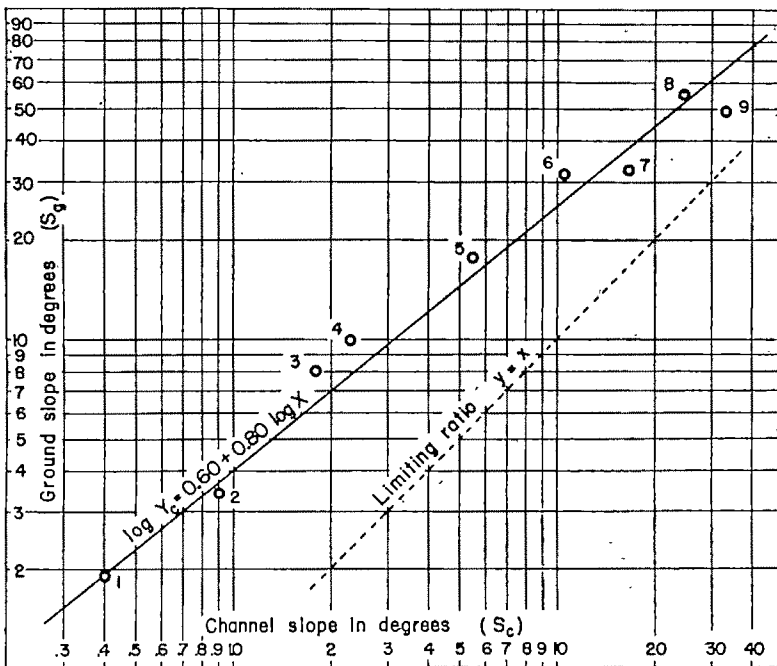


Fig. 8. Slope ratio, $\frac{S_g}{S_c}$, for nine maturely dissected regions. 1. and 2. Grant, La., 3. Rappahannock Academy, Va., 4. Belmont, Va., 5. Allen's Creek, Ind. 6. Hunter-Shandaken, N. Y. 7. Mt. Gleason, Calif. 8. Petrified Forest, Ariz. 9. Perth Amboy (clay fill), N. J. All data from U. S. G. S., A. M. S. or special field maps.

in the humid climates. The thinly vegetated areas would require relatively steeper channel gradients for the transportation of the greater quantity of detritus. In the two cases lying to the right of the line the channel slope is high in proportion to ground slope. While this could easily be merely the result of chance sampling, it is in agreement with the deduced behavior. On the other hand, well-vegetated slopes in the humid climate would tend to supply less detritus because of the increased surface resistivity and infiltration capacity, and would be associated with relatively lower channel slopes. As if to verify this deduction, points 3 through 6, representing humid regions, lie to the left of the line of the estimating equation. As this could readily be the result of chance, the observation merely makes more intriguing the prospect for a more adequate investigation of this phase of equilibrium relationships.

Comparison of Slope Data of Maps with those of Field Observations.—The problem of reliability of slope readings taken from maps in comparison with readings made at the same locations in the field is an important one, inasmuch as the labor and cost of the first method is only a fraction of the second. The writer was inclined to suppose that the most recent maps of the Army Map Service on a scale of 1:25,000 and of the U. S. Geological Survey on a scale of 1:24,000 made by photogrammetric methods would give results equal to ground observations.

For test purposes the Shandaken and Hunter, N. Y. quadrangles of the Army Map Service were selected. In the field the writer walked along the side slopes of five drainage basins, following trails marked on the maps. The maps have been prepared from air photographs. Planimetric detail seemed remarkably good when checked in field use. The drainage basins are large, the slopes long and of relatively simple, smooth character. A total of 60 field readings was taken, or about 12 in each basin. These readings were spaced from 50 to 150 yards apart. A frequency distribution diagram of these data is shown in figure 9, lower half.

In the laboratory slopes were measured from the contours along the same stretches of the trails. Approximately the same number of readings, 58, was taken, and while these are sampled from zones corresponding to those in the field, they are equidistantly spaced and do not coincide exactly with the field

readings. A frequency distribution diagram of these readings is shown in figure 9, upper half. A comparison of statistical measures of the two distributions is given in table 3.

TABLE 3

Summary of field and map data of five drainage basins,
Hunter and Shandaken Quadrangles, N. Y.

DRAINAGE BASIN	FIELD DATA		MAP DATA	
	$\bar{X}$		$\bar{X}$	
Hunter Brook	27.7°	$N=60$ $\bar{X}=32.69°$ $s=6.24°$ $s_{\bar{x}}=1.07°$	26.9°	$N=58$ $\bar{X}=30.72°$ $s=6.20°$ $s_{\bar{x}}=0.81°$
Becker Hollow	30.0°		30.7°	
Taylor Hollow	32.8°		28.3°	
Notch Lake Hollow	33.4°		31.9°	
Shanty Hollow	35.5°		34.4°	

Examination of the histograms and summary table shows that the field distribution has a higher degree of irregularity

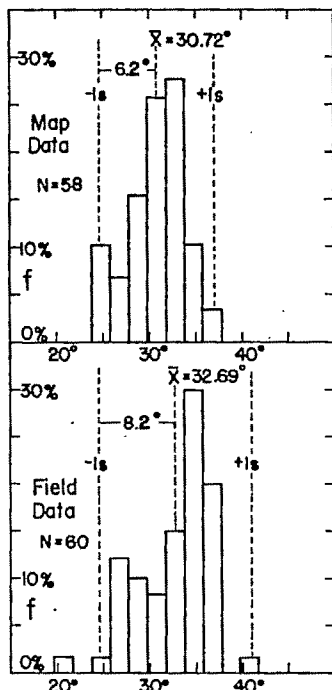


Fig. 9. Histograms comparing field and map samples of slope angles from the same drainage basins. Shandaken and Hunter, N. Y. quadrangles, A. M. S. 1:25,000.

than the map distribution. Dispersion is greater in the field data, with an estimated standard deviation a full 2° greater and with two end classes which are not present in the map data. It appears that use of the map tends to reduce the dispersion and remove irregularities. This might be expected if the drawing of contours in preparation for reproduction results in increasing the degree of parallelism present in the original contours.

The field data are strongly bi-modal because, of the five drainage basins used, two have low but similar means; the other three are relatively high. Note that while the map data also show a bi-modal tendency, it is greatly reduced; the sequence of means is not in quite the same order as in the field data. The greater homogeneity of the map data is again apparent.

Of greatest interest is the difference in means, a whole 2° . We might at first suppose that the processes of mapping and map drafting have caused a reduction in slopes, through the process of drawing the contours evenly spaced on the map, even where steeper and less-steep portions of the slope are actually present. This would tend to lower the angle read from contours alone.

Are the field and map means significantly different? To test the difference, the ratio of the observed difference to the standard error of the difference (Croxtton and Cowden, 1946, p. 819) was computed as follows:

$$\frac{x}{\sigma} = \frac{\bar{X}_1 - \bar{X}_2}{\sigma \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{n}}} = 1.462$$

On the normal curve this value of $\frac{x}{\sigma}$ lies at such a position that the area under the tail of the curve is 0.07. The difference is therefore not significant but the level of significance is not convincing. We can make the following statement: Even if the map is an exact replica of the field topography, we should expect a difference in means of any 2 samples of this size to be two degrees (1.97° exact) or more in 15 out of 100 times because of chance variations in sampling alone. Hence we cannot say that the map is inaccurate. Even if a very significant difference were present, it would not necessarily mean that the map were at fault. Differences resulting from the map

and field methods of reading slopes might cause the observed differences in means.

In conclusion, we may say that while a fairly close agreement exists between field slope data and those taken from the best available topographic maps, the inconsistencies are of too great an order to permit significance studies between small groups of field and map data. It is advisable to use only the one type of data, preferably the field observations where these can be had.

A Tentative Classification of Graded Erosional Slopes.—As a result of frequency distribution analysis and field study of slopes in a wide range of localities, the classification of erosional slopes into three general groups seems feasible:

(1) *High-cohesion slopes.* Slopes underlain by cohesive, fine-textured materials such as clays or clay-rich soil or by strong, massive bedrock, such as granite, schist or gneiss tend to have means in the range 40 to 50° and sometimes higher in regions of strong relief. These slopes are higher than the angle of repose of the loose, dry fragments of the same materials, so that taluses of lower surface angle may accumulate at the slope base where material rolls or slides down the slope and is not swept away by streams. These steep slopes are subject to occasional rapid flowage and sliding movements of the soil or surficial layer following torrential rains. Where the slope has a thick soil of weathered, clay-rich material resting on a resistant, massive crystalline rock, a debris-avalanche may strip off the entire layer, exposing a slope of bare rock (Bryan, 1940, p. 262-263; Freise, 1938).

Examples of high-cohesion slopes are found in badlands, such as the Petrified Forest, New Mexico, or in eroded clay dumps along the Raritan River, New Jersey. In the Verdugo and San Rafael Hills of the California Coast Ranges are examples of slopes of similar steepness where a soil layer with moderate vegetation rests on deeply decomposed diorite or metasediments. Bailey (1948, p. 304) has described stable vegetated 60-degree slopes underlain by fine-textured soils with well-developed profile. He attributed the high angle to binding and protective action of vegetation, principally grass. Examples where bare, hard, massive crystalline rock forms the slope were seen in the Blue Ridge in North Carolina.

Thus steepness of slope, alone, without regard to scale of

slope length or drainage density, can exist under a wide variety of lithologic conditions. There is the common property of maintaining a slope angle above that of the angle of repose of coarse fragmental materials because the slopes possess a high degree of cohesion or strength. All seem to require also that a steep-gradient stream system in process of vigorous corrasion be present.

Bryan has pointed out (1940, p. 263) that for steep slopes of the tropical regions there is nothing to indicate that the slopes should flatten with time. We might reason that, so long as a steady state prevails in which the streams are corradng their channels and constantly removing the detritus from the slope base, conditions of vegetation, climate and lithology remain constant, the slopes would maintain a fairly constant angle in equilibrium with the other factors. However, just as graded streams gradually regrade their profiles to lower gradients with generally decreasing land relief, the contributing slopes might be expected to be gradually reduced in gradient, the system maintaining a steady state through any given short period of time.

(2) *Repose slopes*. Slopes which shed loose, coarse rock particles may be controlled by the angle of repose of those materials provided that vigorous stream corrasion into the slope base promotes the maintenance of the maximum or near maximum repose angle. Meyerhoff (1940, p. 251) seems to have included this type of slope in the term *gravity slope*. Bryan (1922, p. 43) terms certain desert mountain slopes *boulder-controlled slopes*. He states that they are commonly in the range 30-35° and that the grade of the slope is the angle of repose of the average-sized joint fragment.

Repose slopes are illustrated by certain drainage basins in the Catskill Mountains (see figure 9) where a coarse layer of angular sandstone and conglomerate mantles slopes whose mean was found to be 32° in five first-order drainage basins.

The term *talus-slope*, referring to slopes of slide rock accumulation made by accretion of particles rolled or dropped from a higher source, should not be confused with repose slopes here described. The latter are essentially erosional, having only a thin veneer of loose particles over the parent bedrock.

Erosional repose slopes are observable in gravel pits where glacial-fluvial sands and gravels are being excavated. Left

undisturbed, a fresh vertical cut into a gravel bank will recline to a straight slope equivalent to the angle of repose of the loosened particles, but composed of the almost bare, undisturbed, bedded sands and gravels. On this slope, which merges into a true talus at the base, particles will just slide or roll when dislodged from the parent mass. Laboratory analysis of angles of repose in fragmental materials (Van Burkalow, 1945) shows that repose slopes have distribution characteristics similar to the valley slopes described in the present paper.

Slide-rock slopes might be expected to maintain a constant angle as a region is progressively denuded, provided that the streams maintain a vigorous corrasion which saps the valley walls and maintains the maximum angle of the slide-rock fragments.

(3) *Slopes reduced by wash and creep.* Where channel corrasion is greatly reduced and channel gradients are low, due to onset of a late-mature stage, slopes are not maintained at the maximum angle by basal corrasion. Here sheet-erosion, rain beat and creep reduce the slope to angles well below the angle of repose. Bryan (1922, p. 46) terms these slopes *rain-washed slopes* and states that they are developed on fine-grained materials, readily subject to removal by rain-wash. Meyerhoff (1940, p. 251) terms these *wash slopes* and states that they seldom exceed 15° . He regards them as secondary forms which replace the steeper varieties by encroachment at the base. In the W. Penck system these would be classed as *Haldenhänge*.

Examples of slopes reduced by wash and creep were found to have means ranging from 20° to as low as $11\frac{1}{2}^\circ$ (see fig. 2, A, B). It is postulated here that the slopes were reduced gradually in angle as the relief of the region diminished and stream gradients declined. Some evidence favoring a gradual decline of slope angle rather than replacement of a steep slope by a distinctly lower slope is discussed in a later section.

Summary Statement.—The application of standard methods of frequency distribution statistics to study of slope angles is of value in two principal respects: (1) It provides a standardized quantitative method of describing the characteristics of maximum slope angles within a small area, although it does not rectify fundamental errors of judgment made in the

sampling process. (2) It provides a tool, through the method of significance of difference of sample means, of evaluating the results of field measurements and thereby prevents the drawing of unwarranted conclusions from numerical data. At the same time it may give confidence in certain conclusions based upon truly significant differences in sample means.

The measurement and analysis of real landforms is an inductive method, contrasting strongly with the purely deductive projective-geometric treatment of slopes used by Lawson (1915) and Putnam (1917) and recently revived by Bakker and Le Heux (1946). The latter method lays great stress on precision attained by setting up initial assumptions and deducing the slope profile to be expected. Whether the initial assumptions or deduced profile development bear any resemblance to real landforms is dubious at best, because only one process, out of several acting together, is selected for analysis.

(To be continued)

THE CHEMICAL KINETICS OF THE KATMAI ERUPTION

C. N. FENNER

PART II

ANALYSES OF PUMICES

Probably the most convincing proof of the processes at work in the magma is provided by the analyses of the pumices.

In preparation for analyses, if the field sample consisted largely of lumps of pumice, many lumps were picked out and ground to fine powder. The lumps in any sample show considerable variation among themselves because of imperfect magmatic mixing, and an endeavor was made to take a representative sample. Actually, the attainment of this objective was not thought to be of the greatest importance. Each lump of pumice was believed to be in effect the result of mixing of two end members—the new magma and the old rocks of the crater—and though the composition of the sample taken for analysis might depart from that of the sample as a whole, it should still have a composition proportional to a mixture of the two, or, in a geometrical construction, it should lie on the lines between the two ends. The most important point was to determine if this was true. Nevertheless an effort was made to have the part taken for analysis represent the stratum of ashfall in which it occurred.

The thinner strata were generally of finer grain. The material of each of these was simply mixed, and a part taken.

Twelve of the thirteen layers of ashfall at Camp IV were analyzed. No. A-184, a 6 mm. layer, was left out as being insignificant. These analyses are given in table 1. Eleven of the twelve analyses, recalculated to 100 per cent after omitting water and minor ingredients and with all iron calculated as Fe_2O_3 , are plotted on the diagram figure 3. No. A-187 is not included. It is a 35 mm. reddish-brown and purple sand or mud at the top of the ashfall. Its composition is much out of line with the other layers. What it represents is uncertain—possibly a wind-blown dust.

In an article published several years ago (Fenner, 1926, p. 700) the compositions of a large number of older igneous rocks of the Katmai region, together with A-175 of the 1912 eruption, were plotted on a similar diagram. The indicative

points of these analyses were shown to lie close to straight lines. If now the lines of the older diagram be superposed on figure 2, all the points of figure 2 are found to lie very close to them. The lines of the older diagram would probably be accepted

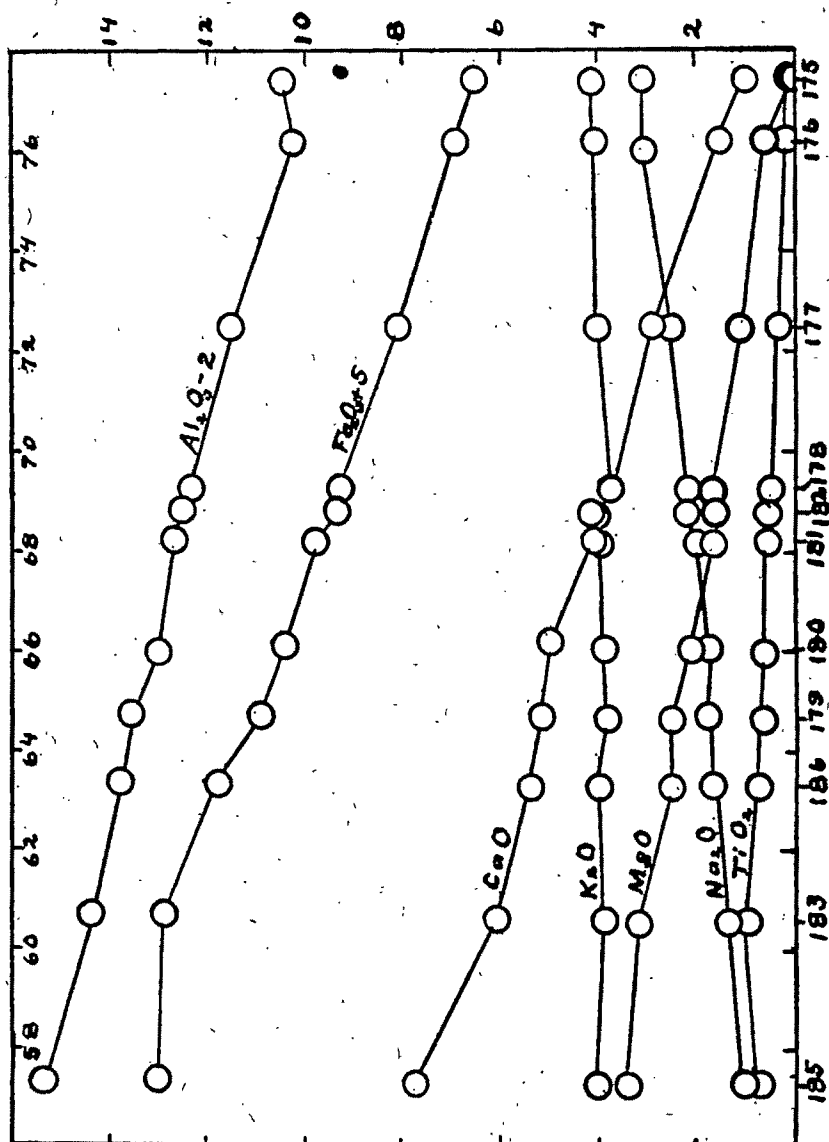


Fig. 2. Diagram of analyses of pumices in successive layers of Katmai ashfall.

without question as representing the average lines of variation of the pumices of the 1912 eruption. This should be expected if the rocks of the crater walls had a composition in accord with the lines of variation of the old lavas of the region and if the pumices represent the assimilation of these wall-lavas by the new magma. Under any other supposition the agreement would be extraordinary. A similar but more exact and convincing demonstration was worked out as follows: The average composition of all the strata of the ashfall was calculated by taking the composition of each stratum, giving it a weight in proportion to its thickness, and combining the whole. The results of this calculation are included in table 1. This average composition was then plotted on the straight-line diagram of older rocks, Alumina was found to be 0.38 per cent low, ferric oxide 0.19 per cent low, and each of the other constituents, magnesia, lime, soda, potash, and titania, showed less than 0.1 per cent discrepancy.

This agreement, I think, is remarkably good. Several factors might have prevented such close agreement. The lavas of the peak that were assimilated might not have had quite the composition that would conform to the straight-line diagram, winnowing by winds during the downfall of the ash might have had a selective effect, incorporation of sediments might have caused departure, and there might have been analytical errors. We thus have the strongest confirmation that the pumices are simple mixtures or assimilation products of the old crater walls and the new magma.

In the composition of the pumices there is little or no indication that the sedimentary rocks through which the volcanic conduit rose made any important contribution to the pumices, yet it might be supposed that these rocks would be attacked and assimilated as readily as the lavas. Why were they not? I believe the answer involves one of the fundamental theses of this article and gives it strong support. It is that the exothermic reactions by which the magma was enabled to assimilate the wall rocks were developed only in the upper portions of the lava column as it lay in the crater—those portions from which gases were able to escape and set in motion the mechanism of exothermic internal reactions.

We may draw another important conclusion from the analyses. We have evidence that sedimentary rock was not assimilated

to any important degree and we know that no great quantity was thrown out mixed mechanically with the pumices. What, then, became of the sedimentary rock that occupied a great part at least, of the space where there is now the huge crater pit? We may answer with considerable assurance that it collapsed into the depths after the eruption was over.

In early papers I had touched upon this problem, but the evidence then at hand did not seem sufficient to answer the question definitely. I was inclined to the view that sedimentary as well as igneous rock was involved in the large amount of contamination that the pumices show. Dr. Howel Williams, in correspondence, favored cauldron subsidence at Katmai because of the many instances of this action that he had found in great calderas in various parts of the world (1941). Mount Katmai can now quite certainly be added to his list.

Additional evidence is provided by consideration of the Katmai incandescent tuff-flow. This tuff lies on top of the Katmai ashfall (plate 1), and therefore was the final act of ejection. If the present vast caldera had existed at this time the material of the tuff-flow would have had to fill it before it spilled over the rim, and this is hard to imagine. Furthermore, the depression (glacial trough) on the present southeast rim that would have been the outlet channel for the tuff if present conditions existed at that time, is matched by a similar depression on the northwestern rim, at no higher elevation, that would have offered equal opportunity for overflow. This northwestern sag would have led part of the overflow down the western side of the mountain into the Valley of Ten Thousand Smokes, along the course that we took in our 1923 ascent of the mountain. We saw no evidence of the tuff on our ascent on this side, whereas on the southeastern side it is plainly evident. The inference is that until the end of the eruption, including the final outburst of the Katmai incandescent tuff, the present caldera had not been formed, but that some remnant of the peak in which the crater lay was still in existence, and that its configuration was such as to direct the flow of incandescent tuff to the southeastern side. This condition may also have been a factor in causing heavier ashfall on the southeastern side.

Calculations have been made from the analytical data now on hand to determine in what proportions the older lavas were assimilated by the new magma. Since the composition of the

pumices fits (very closely) the older diagram of straight lines between the two end members, we have a simple geometric relationship such that any one of the constituent oxides is proportionately representative of any other, and we might use any one of them in calculations. Silica percentages will thus be used as most convenient and least likely to exaggerate minor discrepancies.

In the calculated composition of *pumices as a whole* (table 1) a silica content of 69.18 per cent was found. The new magma, A-175, had 77.43 per cent silica (on a volatile-free basis), and the mafic rocks that it assimilated have been assumed (from the character of their phenocrysts) to have had 54 per cent silica.

Let x = amount of mafic rocks assimilated.

Then $54x + 77.43(1-x) = 69.18$.

$\therefore x = 35.4$ per cent of assimilated mafic rocks and 64.6 per cent of new magma, A-175, in the *average pumice*.

Part of the assimilated rock was incorporated directly in the melt and part was left undissolved as phenocrysts (xenocrysts) of the contaminated product.

Although the new magma, as it first appears in the lowest stratum (A-175) of the ashfall, shows no contamination itself, its exothermic reactions doubtless helped as a source of heat, supplied both to the rocks engulfed in it and to wall rocks against which it lay and which subsequently became engulfed. Likewise, gases given off, with their mutual reactions not yet completed and still reacting vigorously with each other exothermically, added to the effective heat supply.

It is of interest to learn how much of the incorporated mafic rock was actually dissolved by the new magma and how much was left undissolved. It is clear from the petrographic studies that the groundmass of the old lavas and also the aphanitic lavas as a whole were quickly dissolved, but that the phenocrysts were less rapidly attacked. Calculations were made on the pumice of *layer 180*. This layer is the thickest of the series and one of the most homogeneous. It is somewhat more mafic than the pumices as a whole, but the results, suitably modified, are applicable to all.

As a first step, using the same form of equation for A-180 as was applied just above for the average pumice, but using the silica content of A-180 (66.12 per cent on a volatile-free basis),

calculation gives 48.12 per cent of old rocks incorporated, that is, partly dissolved and partly left as undissolved phenocrysts (compared with 35.4 per cent in pumices as a whole).

In the next operation the amount of mafic rock actually dissolved in the glass of A-180 is to be determined. This glass has an index of about 1.489, though striae of slightly higher index attest inhomogeneity. In ordinary calc-alkalic rocks an index of 1.489 in a glass indicates a composition of about 72 per cent silica.

Then

$$54x + 77.43(1-x) = 72$$

$x = 28.1$ per cent of mafic rock dissolved in the *glass of A-180*. Later, by another calculation with different data, this will be confirmed.

In order to obtain further information and to check data previously obtained a specific gravity separation and partial analysis of the products were applied to pumice A-180.

A portion was crushed to pass 100-mesh and a separation was made in a mixture of methylene iodide and benzol. It was hoped that a fairly clean separation into heavy and light fractions could be made in this way, but such separations are difficult when the specific gravities approach each other closely or overlap. The light fraction obtained was found to have a considerable amount of heavy minerals, mostly feldspar, estimated at 10 per cent, and the heavier fraction contained an estimated 5 per cent of glass. Although the separation was not clean, approximations were obtained which are believed to be fairly close to correct results. Certain circumstances or coincidences are favorable for approximate calculations. In a basalt or basaltic andesite of 50 to 55 per cent silica the feldspars alone, the remainder of the rock without the feldspars, the groundmass alone, and the remainder of the rock without the groundmass, all are likely to have a silica content not differing greatly from 50 to 55 per cent.

A determination of alkalis in the heavy fraction of the gravity separation gave 3.61 per cent Na_2O and 0.614 per cent K_2O . (See table 4.) Since there is a little glass in this heavy fraction, and this glass carries alkalis contributed by A-175, the figures should be modified in order to obtain the amounts appropriate to the heavy minerals alone. This correction is very small, but the final figures become 3.26 per cent Na_2O and

0.55 per cent K_2O in the heavy minerals. When these figures are plotted on the straight-line variation diagram, they fit at 53 to 54 per cent silica. They become increasingly inconsistent as we move away from these figures.

TABLE 4

Partial analyses of heavy and light fractions of specific gravity separation of pumice A-180.

	<i>Light Fraction</i>	<i>Heavy Fraction</i>
SiO_2	69.78	
Na_2O	4.07	3.61
K_2O	2.11	0.64

This result is confirmed by another calculation in which wholly different data are used, as follows: The trend of potash content of the pumices shows a regular decrease of silica. When, by a test calculation, silica is taken as 50 per cent, potash has become a minus quantity. This is clearly impossible; therefore the silica content of the assimilated rocks must have been more than 50 per cent. The corresponding upper limit is found from the composition of the pumice A-185. This pumice contains 57.59 per cent silica (volatile-free basis) and is the most basic of the ashfall strata, but the pumices in it are evidently of variable composition. Some lumps are gray, with many dark xenocrysts, and others are almost pure white and are nearly free of xenocrysts. Partial analysis of these latter give the values of 185X of table 1, corresponding nearly to the purest pumice A-175. This is of much interest in itself, as demonstrating the continuous welling-up of fresh magma. Its application here is that it shows that A-185 would be more basic if its content of A-175 could be removed. Therefore, the undiluted basic rock carried less than 57.59 per cent silica. Thus we have bracketed the silica content of assimilated basic rock between 50 per cent and 57.59 per cent, and the original assumption of 54 per cent is closely confirmed.

The *light* fraction of the specific gravity separation of A-180 was a mechanical mixture of 10 per cent (estimated) heavy minerals (mostly basic feldspar) of 54 per cent silica content with 90 per cent glass. The glass is a solution of mafic rock in the new magma A-175. A special analysis (table 4) showed this light fraction to contain 69.78 per cent silica.

Let x =silica percentage of the glass alone.

Then $5.4+0.9x=69.78$.

$x=71.5$ per cent silica in glass of A-180. From the refractive index of this glass a silica content of 71 to 73 per cent was estimated in a previous calculation, and on a basis of 72 per cent silica it was calculated that 23.1 per cent of mafic rock was dissolved in the glass of A-180.

With the data now on hand it is further calculated that about 53 per cent of the pumice of A-180 is glass.

Finally, in our study of A-180, we have the partial analysis of the lighter fraction of the specific gravity separation listed in table 4, showing 69.78 per cent silica, 40.7 per cent soda, and 2.11 per cent potash. This fraction consists mostly of glass but partly of feldspar crystals. Since both the feldspar crystals and the mafic rock as a whole have approximately 54 per cent silica, this light fraction is a mixture (partly in crystals and partly in glass) of the magma A-175 with various substances of 54 per cent silica content. When the analytical results are applied to the straight-line variation diagram, the soda and potash of the analysis should fall at the points where the ordinate erected at 69.78 per cent silica intersects the lines for soda and potash of the diagram. When so tested the correspondence is found to be 4.07 per cent compared with 3.90 for soda and 2.11 compared with 2.23 for potash.

In several ways we have found in the analyses confirmation of the belief that the pumices are products of the assimilation of great quantities of the old mafic rocks of the volcanic crater by the new rhyolite magma A-175. Following is a brief recapitulation of the chemical evidence and its significance.

1. The lines of variations of composition of the pumices, as shown in figure 2, correspond very closely with the corresponding diagram of older igneous rocks of the Katmai region.

2. The composition of all the pumice strata taken together likewise falls almost exactly on the older diagram.

3. From these correspondences it is concluded that sedimentary rocks did not enter to a perceptible amount in the hybridization—only the basic lavas of the mountain top in which the crater lay.

4. It follows further that the evolution of heat for assimilation was essentially a near-surface effect and was not developed to a great depth of the new lava (that is, it did not penetrate down to the horizon where the lava was in contact with sediments).

5. This last is in accord with the further fact that explosivity affected only the upper portions of the lava column at each outburst.

6. The formation of the present great caldera was caused by cauldron subsidence—solution of sediments was little if at all contributory.

7. Indices of refraction of feldspars indicate that the old lavas contain 54 per cent silica.

8. From silica content (by analysis) of average pumice and silica contents of new magma and old rocks respectively, the average pumice is found to be made up of 35.4 per cent of assimilated mafic rocks (partly dissolved in glass and partly left as undissolved xenocrysts) and 64.6 per cent of new magma A-175.

Special computations were made on the pumice of layer A-180 of ashfall.

9. On similar data as for the average of all pumices A-180 consists of 48.3 per cent of old rocks (dissolved and as xenocrysts) and 51.7 per cent of new magma A-175.

10. From index of glass of A-180 as evidence of a silica content of 72 per cent it is found that the glass of A-180 contained 23.1 per cent of mafic rock dissolved in it.

By making a specific gravity separation in A-180 and partial analyses of the fractions, further data were obtained.

11. Determination of soda and potash in the heavy fraction of A-180 gave results that fit the variation diagram at 53 to 54 per cent silica, thus confirming the previous conclusion No. 7 from different data.

12. From the silica content of the light fraction of A-180 we find that the glass contains 22.2 per cent of mafic rock, compared with 23.1 per cent as found under No. 10 by another method.

13. It is found that about 53 per cent of A-180 is glass.

14. The general diagram (fig. 2) shows fluctuations of relative amounts of old rock and new magma in the pumices. There is increasing quantity of old rock from A-175 to A-179, decreasing quantity to A-182, increase to A-185, and decrease to A-186. These fluctuations are attributed to conflicts between amounts of old rocks assimilated and fresh supplies of A-175 welling up into the crater. This is confirmed by the heterogeneous character of the pumices and the presence of white pumice in

each layer; further by the fact that white pumice picked out of the most basic sample (A-185) and analyzed (185X) has nearly the composition of the pure rhyolite.

15. Partial analysis of the light fraction of the specific gravity separation of A-180 (table 4) shows amounts of silica, soda, and potash fitting the straight-line diagram of older rocks.

I submit that this evidence is an extraordinarily concordant confirmation of the thesis of this article. To be added to it is the field evidence that has been cited of the characteristic of the pumices in the ashfall and the petrographic evidence by which the actual process of solution of xenoliths is made visible and the xenocrysts of the pumices are traced directly back to the phenocrysts of the old lavas. There seems to be no escape from the conclusion that the pumices are the result of the assimilation of great quantities of the old rocks of the crater in the new magma. If this evidence is not sufficient, there is more to be cited in the phenomena of Novarupta and of the incandescent tuff-flow in the Valley of Ten Thousand Smokes.

A short description of the results of two other analyses of Katmai products remains to be given.

Sections of the ashfall at two sites in Katmai Valley have been described. Three others studied were of essentially the same character, except that the thickness of strata decreased in going southward. Among the samples of these taken, one A-505, corresponded in position in the section and in makeup to A-181. An analysis was made as a check and is given in table 1. The composition is almost a duplicate of A-181, although this stratum was of heterogeneous composition like all the strata of the ashfall. It was mostly a light-gray pumice, but varied from a white pumice with an index of 1.487 and rare phenocrysts of sodic feldspar to a dark pumice of index 1.505 and many phenocrysts of pyroxene, feldspar (labradorite), and iron ore.

The horseshoe island on the floor of Katmai crater was evidently formed by a small extrusion of lava after the cauldron subsidence took place. The analysis of this lava is given in table 1 as A-547. This does not fit the general diagram as well as the analyses of pumices do. The type is not very different, but it departs from the composition that a straight mixture of the new magma and the old rocks of the crater give, and in that

way it does not conform with others. This hardly seems surprising. If it is a hybrid rock, the conditions of hybridization were different from what they had been previously. After the collapse of the crater any lava that found exit at the surface had to work its way through a mixed mass of broken and crushed igneous rocks and sediments. Petrographic study of a thin section does not give much further information. A glassy matrix of index 1.490 incloses numerous phenocrysts of feldspar, pyroxene, and iron ore. The feldspars are somewhat variable, but most have a composition of about An_{44} .

THE INCANDESCENT TUFF-FLOW OF THE VALLEY OF
TEN THOUSAND SMOKES

In the Valley of Ten Thousand Smokes occurred the great flow of incandescent tuff and the violent explosive activity of the parasitic volcano Novarupta. The processes of assimilation and hybridization here are of the same nature as those described in connection with the ejecta of Mount Katmai, but the evidence is, in some ways, even more clear. In some of the phases of activity assimilative action was less intense and halted at a point where digestion was only half completed. If assimilation had gone only a little further in the main crater of Katmai, the more striking evidences of inhomogeneity would have been pretty well wiped out, but among the products of Novarupta and the Valley^{*} vents the inhomogeneities are so evident that they cannot be missed.

The incandescent flow or flows of the Valley apparently constituted the first major outburst of the eruption, for they are covered by a layer of ash from Mount Katmai. In the lower (southwestern) part of the Valley this latter deposit is rather thin; in the vicinity of Novarupta it is presumably thicker because of nearness to Mount Katmai, but it is so mingled with the much greater quantity from Novarupta itself that it cannot be distinguished. Near Novarupta the strata of ash are incomparably thicker than anything found close to Mount Katmai, but they decrease rapidly as one moves away from the vent.

The breaking-out of Novarupta and the innumerable lesser vents in the Valley, in an area where no volcanic activity had formerly been present, seems to have been caused by the following succession of events: When the new magma first rose in the

^{*} "Valley," written with a capital V, will be used as a shortened designation of the Valley of Ten Thousand Smokes.

Katmai conduit and before it reached an explosive stage in the crater a portion of it escaped as a sill injected under the floor of the Valley between the nearly horizontal sedimentary rocks that underlie the area. This resulted in fracturing and dislocation in various places (Fenner, 1925). The floor of the Valley was upheaved, the defile of Katmai Pass was broken open, the lower slopes of Mount Trident that face the Valley were badly shattered, a great slice of Falling Mt. collapsed, and Broken Mt. was cut to pieces. From the vents thus produced the great incandescent tuff-flows were poured out. Novarupta was the chief of these vents, and its orifice later became enlarged and it passed into violent eruption. Finally a mass of viscous lava rose from its crater as a dome, about 800 feet (244 meters) in diameter and 200 feet (61 meters) high, surrounded by a high wall or "corona" of ejected pumice and glass-blocks. (For illustrations see Griggs, 1922, pp. 238, 276, 280, 300; Fenner, 1920, p. 588; 1923, pp. 15, 44, 53, 58, 60, 63; 1925, p. 203.)

Vents broke out in both branches of the V-shaped Valley for a distance of 12 to 13 miles (19 to 21 km.), from Mount Trident to Three Forks, and in a branch extending southerly up over Katmai Pass (fig. 1). Probably all were orifices of extrusion of incandescent tuff-flow, and they were sites of intense fumarolic activity for years afterward, but in 1923 most of them had vanished or the activity had become very weak. The magma that rose in them behaved in a similarly remarkable fashion to that in Katmai crater. Instead of exploding at once, it lay for a time quiescent in the vents while it attacked and assimilated the rock with which it was in contact. During this interval magma continued to well up slowly from below and mingle with the contaminated magma. Thus were produced the contrasting layers that are so striking in the myriads of specimens of pumice. A typical specimen of these is illustrated in plate 2. Determinations of silica in this specimen by E. T. Allen gave 74.70 per cent in a white band and 60.40 per cent in a dark band.

There is a great difference in the character of the incandescent tuff between the upper and lower parts of the Valley. In the upper Valley the pumices are in general aspect gray, or even dark brown, and contain large quantities of mafic phenocrysts. In the lower Valley the pumice corresponds to the first ejecta A-175 from the Katmai crater; that is, it is pure white or very

pale buff and contains only a few small phenocrysts of quartz and oligoclase-albite feldspar. E. G. Zies has given a table of compositions of four samples of the pure rhyolite from different sites of the Katmai eruption (1929, p. 56). One is an analysis by Steiger of a pumice collected by G. C. Martin, a second by Zies of a Valley pumice collected by Fenner, a third by Zies of the purest Novarupta rhyolite glass collected by Fenner, and a fourth by Fenner of the first layer of Katmai ashfall, A-175. They are almost identical in every respect. A fifth (unpublished) analysis by E. T. Allen of pumice from the stratum A-175 corresponds.

In the lower Valley occasional specimens of the light pumice show streaks of sharply contrasting dark brown or nearly black color, but the light pumice is much preponderant in this area. Apparently there was very little attack by the magma on foreign materials here, and it is natural to conclude that its underground travel of many miles from the Katmai conduit, in contact with cold walls, exhausted most of its heat reserve.

It is not possible to say whether extrusions from the many Valley vents were approximately simultaneous or not. More exposures by deep stream trenching would be necessary to show in detail how the dark pumices of the upper Valley give place to the lighter pumices of the lower Valley. There is evidence, however, that explosive activity did not cease immediately with the emplacement of the tuff. In many places blocks of consolidated tuff, individually weighing many tons, were ejected from vents, together with a large amount of fragments. This consolidation of the tuff had been effected by the deposition of minute crystals of tridymite and orthoclase by gases evolved from the tuff after emplacement. Induration and late explosive ejection were most prominent in the upper Valley.

The basement rocks of the Valley are sedimentary strata of the Upper Jurassic. Fragments of sediments are fairly plentiful in the tuff, but basic lavas are much preponderant, and this requires explanation. In the upper part of the Valley the slopes of the adjacent mountains are predominantly lavas. Here are Mount Mageik, Mount Cerberus, Falling Mt., Mount Trident, Mount Katmai, and Knife Peak. Large glaciers descend the slopes of Mageik, Trident, and Katmai to the Valley floor, bringing down volcanic debris. Knife Peak now has glaciers only near the summit, but its lower valleys are filled

with morainal material. The final dumping-ground or outwash of all these glaciers was on the Valley floor, so that the vents from which the tuffs issued broke out in the midst of loose morainal material, prevailing of igneous derivation.

J. E. Spurr had traveled through this Valley in 1898 and has described conditions at that time (1898-99, pp. 146 and 147). He speaks of the many glaciers coming down from the volcanoes, and their splendid moraines. A stream on the north-west side of Katmai Pass had cut down at least 100 feet through lava boulders. All along the valley leading to the Pass were stratified gravels "which near the trail across the Pass begin to be filled with great angular boulders. This deposit runs quite up to the foot of the existing glaciers."

This describes the condition in most places in the upper Valley when the new lava broke through. It came into contact with thick superficial detritus of basic lavas, but in some areas the detritus was a mixture of lavas and sediments and assimilation effects varied accordingly.

Descriptions will be given of the character of the incandescent tuff in several areas where the nature of the detrital material that was available for assimilation is reflected in the assimilated product. These will include Knife Creek Valley, Katmai Pass, and the area adjacent to Buttress Mt.

Tuffs in Knife Creek Valley: Knife Creek Valley is the southeastern branch of the Y-shaped upper Valley. Many explosion craters occur here. They reach a maximum diameter of 200 feet or more, and a depth of 50 to 75 feet. The rims of many intersect. Their distribution seems to be at random, except for a tendency to follow the course of the Valley near the northeast side, for two or three miles (1.6 to 2.4 km.). In 1919 Allen and Zies found very high temperatures in some of them (1923, table on p. 104), but in 1923 there was either no emanation or only a little vapor at 98° C. In their walls the lowest material exposed is 10 to 15 feet in incandescent tuff-flow (base concealed; total thickness probably great). This is followed by regularly stratified loose ashfall from Novarupta and Katmai, 25 to 30 feet thick. Surrounding the rims is a thick, irregularly stratified deposit of ejecta blown out of the crater itself (See illustration in Fenner, 1925, p. 197).

The tuff was evidently thoroughly indurated when the explosions occurred and was blown out in large and small blocks.

Its composition reflects the assimilation of moraine of variable composition from the nearby mountains. On the southwest are the sedimentary strata of Baked Mt. and Broken Mt. At the head of this branch of the Valley are the westward-facing slopes of Mount Katmai, sedimentary below, igneous above. Several glaciers descend these slopes. On the northeast side is the great mass of Knife Peak, whose slopes seem to consist altogether of lavas. Several large outwash fans spread from gulches in Knife Peak and in Broken Mt., probably 400 to 500 feet (120 to 150 meters) high in one or two cases. Thus a heterogeneous mixture of debris from sediments and lavas formed the valley fill and was readily available for incorporation in the new magma. Notes taken at various sites showed the following characteristics. At one crater the topmost strata contained great quantities of indurated tuff-flow. "The color of this varies from pinkish-brown to dark-gray. The lumps of pumice in these blocks are light-gray to black."

"Banded pumices are common." At another, incandescent tuff "appears at bottom, under the strata of ashfall and strata of ejecta. It is pinkish-brown and 15 feet+ thick as a maximum. Bottom is not exposed. It is unstratified, and contains gray and black pumice, black glass, red shale (many pieces) and andesites (more or less scoriaceous)." At a third crater, the incandescent tuff is not exposed, but the ejecta contains blocks of it, "dark in color, with much black pumice." At a fourth, 10 feet+ of incandescent tuff is visible, very firmly welded. "Color is brownish-red to chocolate."

The variable but generally medium tones of the incandescent tuff at these sites is to be contrasted with the nearly black color at the next sections to be described, in Katmai Pass. This difference is believed to be attributable to the difference in the character of the detritus available at the two sites.

Tuffs in Katmai Pass: Tuff deposits were studied just within Katmai Pass, a little south of a line between Mount Cerberus and Falling Mt. This site is adjacent to a great flow of dark reddish-brown andesite from Mount Mageik, rising several hundred feet in steep cliffs. Nearby are the lava-covered slopes of Mount Trident. The quoted description from Spurr may be recalled, that in this part of Katmai Pass a stream had cut down 100 feet through lava boulders. This was the environment in which orifices of incandescent tuff-flow broke open.

In reading the accompanying descriptions of very mafic tuff it is important not to lose sight of the fact that the only truly magmatic liquid responsible for the multifarious variations among the tuffs is the rhyolite, A-175, and that it was by assimilation of foreign rock, generally mafic lavas, but, in places, sedimentary rock also, that the varieties of tuff were produced. Even among the most basic-looking tuffs the rhyolite is almost certain to make itself evident by appearing in some amount, large or small, of pure white pumice. When we come to a description of the Novarupta dome we shall see the processes of assimilation in arrested stages.

In the section in Katmai Pass whose description follows, the incandescent tuff is overlain by stratified ejecta from Novarupta. The characteristics of the incandescent tuff are due to its outbreak in the midst of a great thickness of lava boulders; the characteristics of the overlying ashfall are due to the environment at the Novarupta vent a couple of miles away.

The section follows:

A. Lowest stratum. A thickness of 12 to 13 ft. is exposed; bottom not visible. The general appearance is very dark, due both to many lumps of black pumice and to the dark-gray color of matrix of fines. It is practically unstratified, though a suggestion of stratification may be seen along the sides of stream erosion channels. Pumice lumps of 4 to 6 in. (10 to 15 cm.) are common. Much of it is black or very dark brown, with phenocrysts of pyroxene and feldspar in a spongy glass, but light-gray pumice (with some phenocrysts) is also common, and there are many variegated or banded specimens. Fragments of black obsidian (chilled crusts) are present, but no lapilli of sedimentary rock or andesite were observed.

The mass is compact and thoroughly indurated, so that stream erosion has planed off the lumps of pumice and the matrix equally, producing a smooth surface. At the top, for about a foot, this stratum shows yellow and crimson colors, doubtless caused by gas emanations.

Layer A of incandescent tuff is followed by strata of ashfall from Novarupta and probably, to a much less amount, from Katmai. At this stage Novarupta had contributed to the incandescent tuff-flow in the main Valley, and now passed into more violent eruption. Its ejecta were thrown to a distance. The character of the strata of ashfall which follow in this section

Plate 2. Typical banded pumice, Valley of Ten Thousand Smokes.



in Katmai Pass shows that in the crater of Novarupta also rapid assimilation of foreign material was continuing and that eruptive ejections alternated with quiescent periods, during which the chemical reactions within the magma developed.

B. 6 in. (15 cm.) yellow and crimson layer of Novarupta ashfall. Coarse at bottom, with an ordinary maximum of 4 in. (10 cm.). The whole is loose, with not enough fines to fill interstices, but at top the proportion of fines is considerably greater. This layer is not separable from C except by color, and this is a stain, though very prominent and impregnating the pumice thoroughly. Fundamentally the pumice is of the light-gray variety and contains xenocrysts of pyroxene and feldspar. A small amount of lapilli is present—shale and perhaps andesite. Banded pumice was not observed, nor very dark pumice, nor dense glass.

C. 26 in. (66 cm.) light-gray, stained light yellow along certain persistent bands. The make-up is very like that of B, but lacks the deep stain, and proportion of fines is greater. The whole is very loose-textured. It has a pronounced stratification, because of varying proportions of coarse and fine. In B and C and in succeeding layers of the ashfall the lumps of pumice are angular and jagged.

D. 65 in. (165 cm.) thickness variable. The nature and origin of this layer are puzzling. It looks as much like incandescent tuff-flow as like ashfall. In places it contains many very large lumps of pumice up to 2 ft. (60 cm.) in diameter, locally heaped together. Elsewhere lumps of 6 in. (15 cm.) are sparingly distributed. The lumps are very dark brown, light-gray, and variegated. Whether this layer is a second incandescent tuff-flow or Novarupta ashfall, it indicates a great amount of magmatic assimilation but imperfect mixing.

The matrix of fines is dark, and fills interstices pretty fully except in the heaps of bouldery pumice. The top 10-12 in. of the layer is stained crimson. Many small fragments of dark glass are present. Sedimentary rock and andesite are scarce.

E. 6 in. (15 cm.) of ashfall. Is essentially light-gray pumice with phenocrysts, but is stained crimson. Coarse pumice at bottom, more fines at top. This layer is not separable from next except by color. It contains a small amount of obsidian and lapilli.

F. 14 in. (35 cm.) light-gray. Essentially a continuation

of E. Has bands of faint yellow, lavender, and red. It becomes a sand in upper part, and is succeeded by coarser material.

G. 12 in. (30 cm.) light-gray. Like F, but contains much coarse pumice 1 to 2 in. in diameter.

H. 1 8in. (46 cm.) light-yellow. Much coarse pumice 3 to 4 in. (8 to 10 cm.) in diameter. Most of pumice is light-gray, with phenocrysts, but much is light- and dark-banded. Fragments of obsidian and lapilli present.

I. 12 in. (30 cm.) light-gray. Like H but yellow color absent.

J. 24 in. (61 cm.) brownish-yellow. The color (stain) is distinct.

K. 6 in. (15 cm.) of mud. Yellow or brown to lavender.

In this section of Novarupta ashfall the layers do not differ greatly from each other in composition. Although individual pumices show inhomogeneity by their streakiness, assimilation has been so thorough that few xenoliths have survived. The definite stratification indicates waxing and waning of explosive violence.

Another section in Katmai Pass, about three miles south of last, showed at bottom an 84-in. unstratified, compact layer of incandescent tuff-flow exposed in a recent stream cut. It rests upon a mass of loose boulders of reddish-brown andesite, 8 in. to 2 ft. (76 mm. to 61 cm.) in diameter, exposed for a depth of 10-12 ft. It doubtless sifted down among them. Pumice fragments of egg size or more are mixed with fines. It contains great quantities of black pumice, some dark gray and variegated pumice, and some pumice that is very nearly white.

The striking feature is the great amount of black pumice, and its mingling with lighter pumice. The general tone is very dark. On top of this layer of incandescent tuff is about 80 inches of stratified ashfall.

Plate 3 illustrates the character of the incandescent tuff in such deposits as the last two described. The site is a little to the south of Mount Cerberus. The tuff here is highly indurated, and consists of unstratified purplish-brown pumice, with many lumps of gray, black, and variegated pumice scattered through it.

Incandescent tuff near Buttriss Mt.:

The southern arm of the Valley is bounded on the eastern, southern, and western sides by zones of faulting. They are be-

lieved to indicate that the Valley floor was uplifted by the injection of the sill of rhyolite in the underlying strata, and that it collapsed when part of the magma escaped as the incandescent tuff-flow. The fault zone is prominent along the eastern side of Buttress Mt. At a point about three-fourths of a mile (1.2 km.) north of the head of this part of the Valley the broken zone exposes 35 feet (10.7 meters) of incandescent tuff in vertical walls. High cliffs of shale of Buttress Mt. are only one or two hundred feet distant, and the outbreak of the tuff here was probably in a talus slope of shale, but outwash from the Mageik glacier may have brought in some lava. The general color of the tuff is reddish-pink, very different from the nearly black tuffs in Katmai Pass. Lumps of pumice in the fine matrix are white, gray, black, or variegated. The black pumice contains phenocrysts of feldspar and pyroxene in a frothy glass, but neither shale nor igneous lapilli were discernible. The mass is well indurated. As the fault zone is followed northward for three or four miles (that is, away from the lavas of Mount Mageik) the proportion of black pumice seems to decrease.

In the several described sections of the incandescent tuff in the upper parts of the Valley, its character seemed to have a definite relation to the detritus deposits where the outbreaks occurred. Where there was nothing but basic andesite boulders, as in Katmai Pass, the tuff is nearly black, though the upwelling of magma gave occasional white pumices. Where the detritus is largely sedimentary, as in parts of Knife Creek Valley and near Buttress Mt., the tuff is prevailingly light-colored.

In the dark brown or black pumices of the upper Valley the index of the glass generally ranges from 1.520 to 1.530, indicating a mafic composition. Exceptionally it may go as high as 1.540. Associated feldspars range from andesine to calcic labradorite. Pyroxenes and iron ore are present. In the associated light pumices the glass has ordinarily an index of about 1.490. Feldspars in these have a composition of about An_{30} , but stray ones may be as calcic as An_{55} .

NOVARUPTA AND VICINITY

The activity of Novarupta went through three well-defined (though merging) phases (Griggs, 1922, pp. 238, 276, 280, 300; Fenner, 1920, p. 588; 1923, pp. 15, 44, 53, 58, 60, 63; 1925, p. 203). In the first phase it contributed to the incandescent tuff-flow. Then it became explosively active, and

threw great quantities of pumiceous ejecta to distances of several miles. Finally, a mass of viscous magma, nearly free of gases, was pushed up from the vent.

Novarupta is close to the foot of one or more glaciers descending the slopes of Mount Trident. These glaciers are now covered with such a great thickness of ash that the area covered by them and even their number is uncertain. They doubtless deposited much lava moraine here, but Novarupta is also very close to the sediments of Broken Mt. In fact, in its explosions it blew away part of the adjacent cliffs. Thus, both lavas and sedimentary rock became involved in the Novarupta magma.

The heavy ashfall from Novarupta has nearly concealed the incandescent tuff-flow that came from its vent. It is identifiable only in a gully on the eastern side, where about 8 feet of it is exposed. (The bad-land topography of this area is shown in Griggs, 1922, p. 298.) Its color is very dark in the mass, but light-gray and variegated pumices occur in it. It is made up mostly of boulders of pumice a foot or more in diameter, together with large blocks of dark glass. These last contain inclusions of pumice, which presumably had been ejected from the lava pool at an early stage, had fallen back, had been caught in a congealing crust, and finally had been spewed out in the mass of the incandescent tuff-flow.

Above the incandescent tuff is a 6-foot transitional layer of pumice boulders, light-gray, black, and variegated, followed by about 30 feet of ashfall in small lumps, stained crimson along certain bands.

The heaviest deposits of ashfall from Novarupta are in the southeastern to northeastern sector, and they are studied to best advantage on the top of Broken Mt., where fault scarps expose vertical sections of 75 feet or more. (Griggs, 1922, p. 244.)

A large area around Novarupta is shattered by faults. Probably the first dislocations were caused by the injection of the sill, as previously mentioned, but the final adjustments of the shattered ground followed the ashfall and involved these deposits. On the southeastern side of Broken Mt. there is a succession of great faults, with downthrow to the southeast, and with total displacement estimated to be 300 feet. From here a zone of faulting in steps and wedges extends toward the westernmost peak of Mount Trident and continues well up the slopes of

that mountain. This broken country is believed to be the surface expression of the course of the sill advancing from the Katmai conduit toward the Valley of Ten Thousand Smokes.

The Novarupta area has been the scene of intense and long-continued fumarolic activity. In 1919 Allen and Zies found very high temperatures here (1923; pp. 81, 104), and in 1923 certain vents a little to the northeast of Novarupta were still hot enough to melt zinc (419-C).

The strata of ash exposed in the fault scarps of Broken Mt. show varying intensity of explosive action. They contain a considerable variety of ejecta, but, viewed in the mass, there is an impression of sameness from one section to another. The multitude of intersecting faults and their large displacement make it difficult to compare sections. In general, the pumices are very coarse (a diameter of 1 to 2 feet is not unusual) and are of medium or light-gray color, but thick strata of dark brown or nearly black pumices occur, together with the ubiquitous black-and-white variegated pumices that give their unflinching testimony of the manner in which hybridization was effected. Blocks and fragments of andesites and shales are numerous in places and may attain 2 feet in diameter. They occur also inclosed in blocks of black obsidian. These obsidians with or without xenoliths, and in blocks and fragments of various sizes, are common constituents of the ash. A related material resembles bread-crust bombs, but is in irregular masses, up to 8 feet in greatest dimension. One of these is illustrated in plate 4, figure 1. They have an outer crust of black glass, much cracked, and the inner glass has been forced into the cracks. The interior may be of light-colored pumice, variegated pumice, or semi-pumiceous glass. It often contains inclusions of sediments, andesites, basic phenocrysts, pieces of pumice, and fragments of obsidian. In the background of the photo the ground is littered with these ejected masses. These "bombs" and the blocks of obsidian are believed to have been parts of a rigid or semi-rigid crust on the surface of the lava pool, formed during quiescent periods and ejected when activity was renewed. During the final uplift of the Novarupta dome a similar combination of rigidity and plasticity of the lava prevailed (Fenner, 1920, p. 590; 1923, p. 63).

Toward the end of the second (explosive) stage of Novarupta's activity the ejective force became so weak that the

ejecta were barely thrown clear of the crater. A surrounding wall or "corona" was built up. On the west this reaches a height of 200 feet above the general level outside. On the south and east the height increases, and on the north the corona merges with the gouged-out cliff of Broken Mt. Between the corona and the dome is a partly filled moat.

The ejecta in the corona show that with the weakening of the physical forces chemical action also became weak. Assimilation of xenoliths in mild form and welling-up of magma continued, but turbulence had nearly ceased.

Most of the ejected material of this stage is pumice in large lumps but there are also pieces of shale and sandstone and of dense andesite. Blocks of glass are numerous. Much of the pumice is variegated, and reproduces in pumiceous form the banded structure of the dome. It also shows the identical fractures that the variegated pumices of the incandescent tuff-flows and of the ashfall show wherever found. Successive stages of decreasing activity connect the violently ejected variegated pumices with the slowly upheaved banded rock of the dome.

Most of the pumice in the moat is inflated in a normal manner, but some specimens are of intermediate cellular structure between inflated pumices and the very slightly cellular glasses of the dome.

Novarupta differs from the many other vents that were sources of the incandescent tuff of the Valley in being of larger size, in having passed through a much more violently explosive stage, and in that its activity continued into a phase not represented elsewhere by which a dome of viscous lava was extruded. In this third stage assimilation and violent ejection had wholly ceased, but the cessation had been so gradual that much foreign material in various stages of digestion were still present in the stiffening magma, and the whole mass was slowly pushed up by continued accessions of magma from below. As it rose it congealed to a glass, but the upward thrust shattered a great portion of it. Much of the shattered material remained in approximately its relative position, but many blocks dropped into the encircling moat.

The banding gives direct evidence of the mechanism of extrusion of the dome. It is visible around the outer circumference, where masses of rock in place protrude through the disrupted blocks, and the direction of the banding is parallel with the cir-

cular outline of the dome. As the central mass was pushed upward the outer layers were overturned.

In 1919, studies of Novarupta were not carried as far as was desirable before the lateness of the season brought field work to a close. One of the principal objectives in 1923 was to continue these studies in minute detail, as Novarupta provided proof in visual form and on a large scale of the processes of assimilation.

The banding of the dome is expressed in alternations of rhyolite glass, free of phenocrysts except a very little quartz and sodic feldspar, with dark brown or nearly black scoria and glass containing large quantities of mafic phenocrysts. Here are exposed the processes of solution and assimilation by which the mafic pumices and variegated pumices of the Katmai region have been formed.

It is unfortunate that Novarupta is situated in such an almost inaccessible region. Except for its great size it would serve admirably as a museum model, and I believe that if it were available for general study there would be a radical revision of some of the commonly accepted theories of igneous processes. Certainly the introduction of some new thought is needed. The insistence by prominent geologists that all igneous theory must conform to the tenets of crystal fractionation has been stultifying to independence of thought and has delayed for many years progress toward an understanding of magmas and their processes.

In Novarupta an unusual set of circumstances has caused an outbreak of sialic magma highly charged with volatiles capable of exothermic reactions in the midst of detrital accumulations of basic lavas. After a certain amount of assimilation had taken place the process had been halted at just the right stage for critical examination.

In plate 4, figure 2 is shown a characteristic specimen of the banded lava. The point of the pick is near a scoriaceous xenolith, and a number of other xenoliths, both scoriaceous and relatively unaltered, are present. (Other examples of the banded lavas of Novarupta are illustrated in Fenner, 1923, pp. 54, 63; 1926, p. 741; 1944, p. 1085.)

Some of the basic xenoliths are angular and solid and have porphyritic texture. Others are rounded and have become somewhat scoriaceous, though porphyritic texture has not been

lost. Others have become scoriaceous masses from which brown bands trail off. Finally the last indication that the brown bands originate from the xenoliths appears as lenticular swellings.

I estimated that the brown, basic bands form one-third to one-fifth of the quantity of the rhyolitic bands. At the top of the dome (the core of the uplifted mass) the proportion of rhyolite is larger.

In speaking of basic bands the lenses and knots and little-altered xenoliths of andesite are included. They make up a considerable percentage of the basic material.

Generally, the inclusions are obviously basic rocks; occasionally shale or sandstone is found but is rather rare. Limestone has not been observed.

Phenomena of softening and digestion are numerous and plain. They show all stages of transition from distinct xenoliths of basic rocks (generally angular, sometimes rounded, often irregular in a minor way), through those that have become scoriaceous on the periphery and have mingled with the rhyolite; and those that have become scoriaceous throughout and whose melted-off particles have floated away from the parent mass; to knot-like clots of scoria lying along bands of mafic material; and finally to a system of parallel or sub-parallel mafic bands. Though individual bands may be many feet long, each finally tapers off in the all-inclusive rhyolite.

Examples of any of these stages may be found in hundreds or thousands. They are met everywhere in all the rocks of the dome, and the phenomena are so clear that it does not seem possible to suggest any interpretation but that the brown, basic bands that form so large a part of the rock of the dome have been produced by the melting and incorporation of masses of basic rock (with some sediments) which have become involved in the siliceous magma. Nothing hints at any other interpretation.

Though the rhyolite glass is much preponderant over the basic material, small portions of the latter have become so thoroughly disseminated that it is hard to get specimens of the rhyolite that are perfectly free of contamination; nevertheless there is no difficulty in finding large masses in which the amount of contamination is very small, and when the pure glass is analyzed it has exactly the composition of the uncontaminated rhyolite of the eruption in all its phases.

Plate 3. Exposure typical of basic phase of incandescent tuff-flow of Valley of Ten Thousand Smokes.





FIGURE 1



FIGURE 2

The maximum size of unaltered or nearly unaltered xenoliths is seldom more than 8 to 10 in., but some scoriaceous masses are much larger.

COMPARISON WITH VOLCANIC OBSERVATIONS BY OTHERS

Perret was undoubtedly the most indefatigable modern observer of volcanic eruptions. He has written as follows regarding the eruptions of Mount Pelée in 1929-1932, which he studied at close range (1935, p. 88):

"Many regard the liberation of steam resulting from crystallization as the actual cause (of explosions), but observation shows that a rise in temperature precedes the more intense Peléean eruptions while a similar change may be reasonably assumed to precede the lesser manifestations. Heilprin, who was near the summit of the mountain some four hours before the great explosion of August 30 (1902), describes the dome as 'boiling from all its parts, while the roar of escaping steam was appalling,' 'sublime and terrifying.' The photograph, Plate XX of his book, pictures the condition better than any words can do; in it the volcanologist sees the entire mass of lava rapidly heated by countless steam columns rising from underground conduits; conceives of exothermic reactions in the powerfully circulated liquid brought up from the interior of the volcano; and foresees the eventual attainment of a critical condition where the combined energy of the superheated vesicles shall exceed the resistance and the whole grand mass shall explode with cataclysmic violence. Cooling is not a factor in this great combination of causes, the total energy continues to rise."

Perret repeatedly emphasized the *auto-explosivity* of the lava in Peléean eruptions. The lava is not expelled as an inert mass by explosive energy from an external source, "it is the lava itself which explodes" (*op. cit.*, p. 86); and "gas discharge is a process characteristic of the entire mass of discharged lava and continues throughout its course after it leaves the crater" (*op. cit.*, p. 45).

In these excerpts Perret's conception is in close accord with that which I expressed in my papers of 1920 and 1923.

J. W. Judd, studying the effects of the famed eruption of

Plate 4.

Fig. 1. Ejected block from Novarupta.

Fig. 2. Alternation of siliceous and basic bands, Novarupta.

Krakatoa in 1883 (1888, pp. 1-46) had a less clear idea than Perret of the self-explosive properties of magmas, and the manner in which they become manifest. That is not surprising in the state of knowledge of sixty years ago, but his explanation of events seems to be still accepted. He recognized and even emphasized this self-explosive property, but he evidently had great difficulty in understanding in what way an explosion, once started, was brought to a stop while there was still explosive magma at hand. He proposed a mechanism that was physically impossible, but which has been often quoted with apparent approval.

Krakatoa, after preliminary symptoms, seems to have begun actual eruptions from an open vent on May 20 or 21. Booming noises were heard, ashes were ejected, and a steam column was seen. On May 27 an excursion party from Batavia found that the cone Perboewatani was active, "explosions occurring at intervals of 5-10 minutes, and each explosion being attended with the uncovering of the liquid lava in the vent." (Note the agreement with what has been deduced for Katmai). The cavity was about 150 ft. in diameter. A decline of activity followed, but no intermission. Then, from August 11 to the final culmination a heavy ejection of pumice and constant loud explosions were reported. From August 26 to 28 the eruption was in a paroxysmal stage. Even then the discharge was not continuous but took the form of distinct explosions. These were heard 1500 to 2000 miles (2500 to 3200 km.) away.

On August 27 a series of tremendous explosions occurred. There were four principal ones, of which the third was of surpassing magnitude. Judd's interpretation is that by these a breach in the crater walls was made, by which the sea gained access, and the effect of the inrush of cold water was like that of fastening down the safety-valve of a steam boiler. It "caused *a check and then a rally* of the pent-up forces of gases seeking to escape from the molten mass. The serious catastrophic outbursts that produced such startling effects in the air and in the ocean appear to me to have been the direct consequences of the 'check and rally' of the subterranean forces." (*op. cit.*, p. 25).

Verbeek estimated that during this phase some of the coarser fragments were thrown to a height of 164,000 ft. (about 31 miles or 50 km.). Fine dust (films of glass) remained suspended in the upper atmosphere for several years.

Judd's explanation will hardly stand analysis. An obvious objection is that the eruption was pre-eminently of a spasmodically explosive character almost from the first, and during this early period no such restraints as he invokes were present. Moreover, eruptions of other volcanoes (*e.g.*, Katmai) had this same spasmodic character though there was no water at hand to quench them. In Krakatoa (and other volcanoes) each of the violent explosions came to a termination of itself, for the sea certainly could not have gained access while the explosion was continuing in full force.

Evidently Judd did not realize the great thickness of crust that would have been required to restrain the enormous pressures. On what seem to be reasonable assumptions I have calculated that a plate of steel, of a tensile strength of 80,000 pounds per square inch, would have to be 90 to 100 ft. thick to withstand such pressure. A crust of unfissured glass would have had to be 200 ft. thick. It seems out of the question that any such crust could have been formed in the short intervals between explosions.

Although Judd realized that the explosive force resided in the magma itself he did not recognize that this force might not manifest itself immediately unless there was a physical restraint. Probably the fundamental problem that seemed to Judd to require explanation, and that is at the bottom of other explanations in which a restraining cover in one form or another is postulated, is to explain the spasmodic character of explosions, the "check and rally" of Judd. The difficulty arises, I believe, because the evolution of volatiles from a magma has been looked upon as a purely physical process (in the sense of the old distinction between physical and chemical forces) rather than as due to a series of chemical reactions. The phenomena of eruptions indicate that physical restraint is only part of the complex factors and that when an original restraint is removed chemical reactions follow but require time for development. When their chemical nature is realized the door is open for the recognition of a source of heat available for the assimilation of xenoliths and for other effects.

The idea that magmas have power of direct assimilation (much beyond anything contemplated in Bowen's reaction principle) is by no means new. It has been recognized and advocated by various competent geologists, but it has been rejected by a

greater number. The objections have evidently been influenced greatly by certain theoretical conceptions of the nature of magmas that are popular at present. An elaborate structure has been built up on these theories, and recognition of the ability of a rhyolite to incorporate and digest large amounts of basic rock would undermine the foundations of the structure and cause it to collapse. Consequently such ideas have been strenuously opposed. None the less, the evidence that the Katmai magma had this ability is too clear and definite to be brushed aside or argued out of existence. Primarily this conclusion is not based upon the petrographic and chemical evidence or the theoretical principles presented in this article, but upon field evidence so plain that no geologist could miss it. Laboratory investigations have supported this visual evidence, made it more definite, given it quantitative values, localized the site of heat development and assimilation in the upper part of the lava column, and provided a key to explain the formation of the great caldera of Katmai. The phenomena of the incandescent tuff-flow in the Valley of Ten Thousand Smokes and those of Novarupta provide additional information. All the results are in perfect accord with each other.

If, under proper conditions, magmas may exhibit great heat reserves and powers of assimilation, as I believe the Katmai phenomena have made certain, the implications are far-reaching and fundamental. Shifts of internal chemical equilibrium resulting from unloading may be brought into play at different rates—very slowly, as in the intrusion of stocks and batholiths, or with moderate or great rapidity, as in volcanic eruptions. The total heat output will not be affected by the time taken (except to a minor degree), but the effects upon the environment will vary greatly.

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THE FOX CLAY DEPOSIT, UTAH

BRONSON STRINGHAM AND BYRON J. SHARP

ABSTRACT. The Fox Clay deposit is located about 40 miles southwest of Salt Lake City. The clay occurs as a sedimentary lens. Tertiary (?) limestones which lie conformably below and above this bed, dip gently to the southwest. Flat-lying Tertiary basalt flows overlie the southern half of the area.

Differential thermal analysis indicates that the Fox Clay contains more water than typical halloysite $2\text{H}_2\text{O}$. Indices and differential thermal analysis curves vary with the degrees of hydration of the mineral. X-ray powder pictures, however, are constant regardless of degree of hydration, and compare favorably with powder pictures of authentic halloysite. The Fox Clay halloysite therefore contains adsorbed water which so affects all properties other than X-ray as to make it appear to be endellite $4\text{H}_2\text{O}$.

INTRODUCTION

A LARGE clay deposit, locally known as the Fox Clay, situated in the Lake Mountains, Utah, has been mined intermittently for several years. It contains one of the largest potential clay sources so far discovered in Utah, but the clay seriously shrinks and cracks on firing, making its industrial use, without treatment, impractical. It is located about 15 miles west of Provo on the lower southwestern rolling slopes of the Lake Mountains (fig. 1). The maximum relief within the area does not exceed 500 feet and the annual rainfall amounts to about 10 inches.

GENERAL GEOLOGY

The Lake Mountains constitute a north-south trending, typical Basin Range bordered on either side by broad alluvial-filled valleys. The rock units exposed consist of (a) Paleozoic rocks in the Lake Mountains proper, (b) a sequence of Tertiary (?) sediments and volcanic flows on the south-west flank of the range, and (c) Quaternary alluvium and lake sediments in the adjoining valleys. The Fox Clay is interbedded with the Tertiary (?) sedimentary rocks.

The Paleozoic rocks have been folded into a broad syncline with an axis trending northwest, oblique to the mountain range. The Tertiary (?) rocks are only gently folded and though no contact was found, are believed to rest unconformably on the Paleozoic beds on the lower flanks of the mountain.

STRATIGRAPHY

The oldest rock unit mapped in the area shown in figure 2 is a limestone presumably of Tertiary age. Due to the overlap

of valley alluvium, the lower contact of this formation was not found and its full thickness, therefore, is not known, but at least 100 feet of it is exposed. The rock is a fine-grained, dense, tan, unfossiliferous limestone which weathers pale bluish. Microscopic examination shows it to be composed of an aggregate of calcite with an average grain size of about 0.25 mm. Oolites, ranging in diameter from 0.1 to 0.3 mm. are found in scattered patches throughout the aggregate.

The Fox Clay bed overlies the lower limestone conformably and occurs as a lenticular bed with a maximum thickness of 18 feet at the main excavation near the center of the mapped area (fig. 2). It thins rapidly to the south and east, while to the northwest the thickness is not determinable since the outcrop is there covered by valley alluvium.

The bedding in the white clay is expressed by faint pink to brown laminations and banding. Locally, the upper part of the

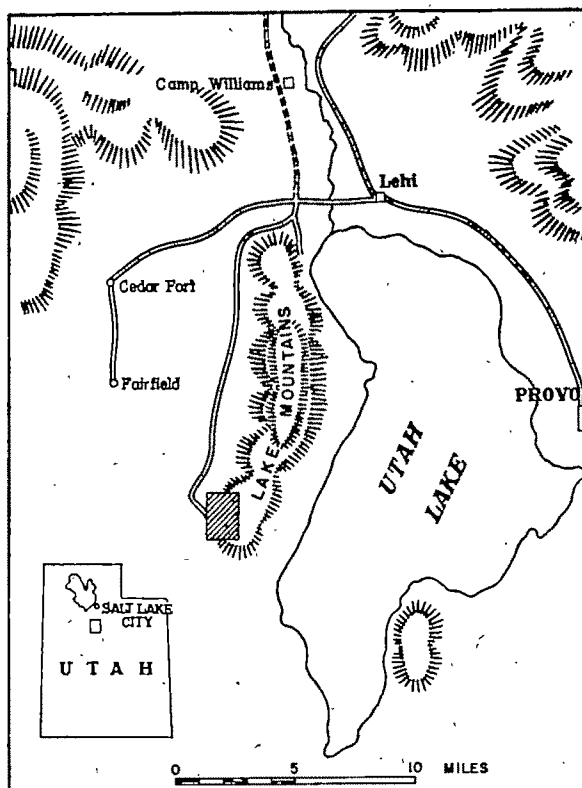


Figure 1. Index map showing the location of the Fox Clay deposit, Utah.

bed is stained by concentrations of hematite in broad pink to maroon bands which make an acute angle with the bedding laminations, giving it a false appearance of crossbedding. The clay is contaminated with varying amounts of detrital quartz, and in the central part of the area near the excavations it contains angular quartz grains up to 5 per cent, while near the borders 15 per cent of quartz in rounded grains is noted locally. A limestone which is identical lithologically to the lower limestone overlies the Fox Clay bed conformably and overlies the lower limestone where the clay lenses out.

A basalt flow overlies these Tertiary (?) sediments with moderate angular unconformity. It rests directly on upper limestone, Fox Clay, and lower limestone in different parts of the area. The flow is about 50 feet thick and caps some higher hills to the south.

STRUCTURE

As stated above, the Tertiary (?) sedimentary rocks are all conformable with each other and maintain a general dip to the southwest of 5° or less. The beds dip locally as high as 40° on two small anticlines whose axes trend north 30° west. These folds disappear under the alluvium to the northwest and die out toward the southeast.

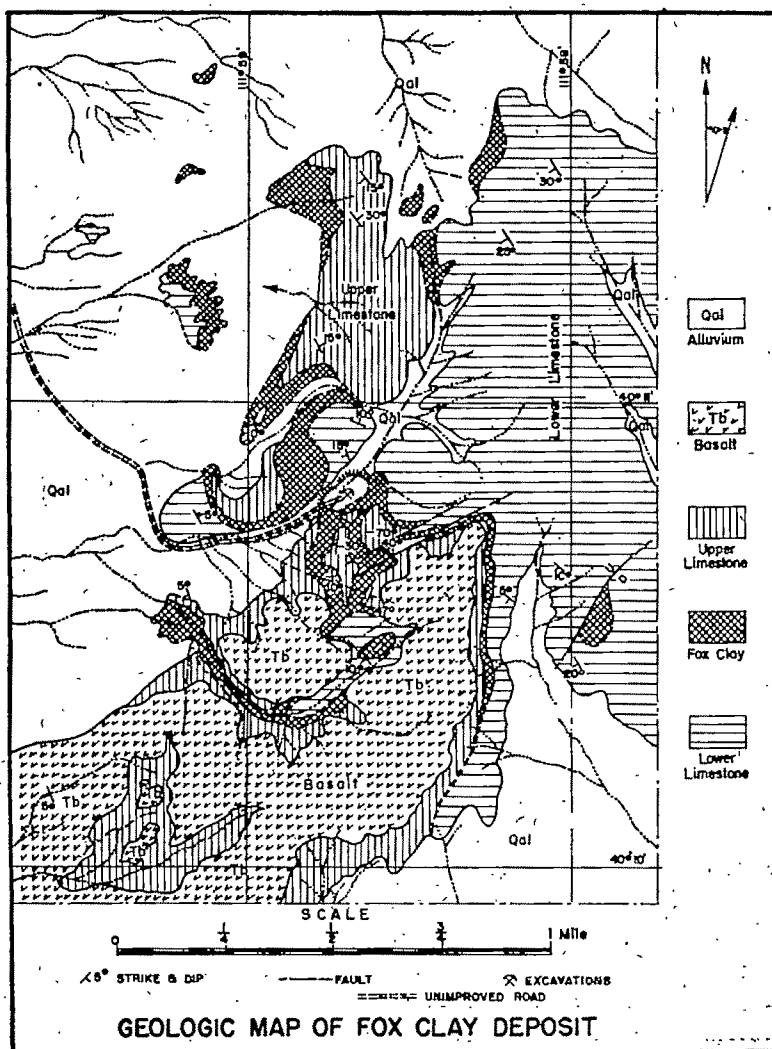
Three faults displace the clay bed. Two of these which are found southwest of the main excavation are parallel and strike north 65° east, with a total displacement of approximately 200 feet.

AGE OF THE CLAY

No fossils of any kind were found within the entire area mapped; hence only an estimate can be made as to the age of these rocks. They have been tentatively assigned to the early Tertiary because of their unconformable relationships to the underlying Paleozoic rocks which presumably were deformed during the Laramide movements. The limestones and clay beds themselves are folded to an extent comparable to that of the Flagstaff limestone of Eocene age in the Central Utah area described by Spieker (1946, pp. 136-137). The Fox Clay is definitely older than the undeformed overlying basalt which is probably the same age as the late Eocene or Oligocene basalts north of the Lake Mountains described by Gilluly (1932, p. 66).

MINERALOGY

Through the kindness of Sterling B. Hendricks of the Bureau of Plant Industry, U. S. Department of Agriculture, a fresh sample of authentic endellite $4H_2O$ from Lawrence County, Indiana, was obtained for purposes of comparison with Fox Clay. Mineralogical examinations, therefore, were made on fresh endellite $4H_2O$ (sample A), dehydrated endellite (sample B), obtained by allowing ground-up fresh endellite to dehydrate at room temperature for 48 hours, untreated Fox Clay



(sample C), and dehydrated Fox Clay (sample D), obtained by allowing ground-up material to dehydrate at room temperature for 72 hours. Examination of these samples by X-ray, differential thermal analysis, electron microscopic and optical methods yielded sufficient information to establish the mineralogy of the Fox Clay.

X-ray Investigations.—Debye-Scherrer diffraction pictures were taken of all of the different samples. Pictures of dehydrated endellite (sample B), untreated Fox Clay (sample C), and dehydrated Fox Clay (sample D), showed lines essentially identical. The d values and intensities of the line patterns of these samples are nearly equal to the d values given for halloysite $2\text{H}_2\text{O}$ (Nagelschmidt, 1934, p. 131, table V, no. III) except for line number 1 which shows a value considerably less than the value given by Nagelschmidt. If this figure had been greater than Nagelschmidt's there would have been reason to think that some excess water for halloysite $2\text{H}_2\text{O}$ was still present between the layers; however, the lower figure for hydrated Fox Clay halloysite $2\text{H}_2\text{O}$ and its similarity to dehydrated authentic endellite $4\text{H}_2\text{O}$, seems to point out clearly that this mineral has the true structure of halloysite $2\text{H}_2\text{O}$ regardless of degree of hydration. Authentic endellite (sample A) was ground, mounted on the X-ray camera and a picture taken all within 50 minutes. This proved to be successful in producing a pattern different from halloysite $2\text{H}_2\text{O}$ and similar to that of endellite $4\text{H}_2\text{O}$ (table 1; A. S. T. M. index; and Mehmel, 1935). The information obtained thus establishes that the Fox Clay, both hydrated and dehydrated, is halloysite $2\text{H}_2\text{O}$ and that the excess water of the hydrated sample is simply adsorbed and does not occupy a position in the structure.

Differential Thermal Analysis Investigations.—Curves were obtained on a number of samples of the material investigated. Conventional apparatus for this determination was used, and the results thus obtained show the same curves for dehydrated endellite $2\text{H}_2\text{O}$ and for dehydrated Fox Clay. Both have a large definite endothermic peak at 600°C . and a smaller sharp exothermic peak at 980°C ., corresponding very well to published curves for halloysite $2\text{H}_2\text{O}$ (Kerr and Kulp, 1948, p. 400).

In the curves for the hydrated samples of each clay the expected large endothermic peak between 100° and 200°C . is present and represents the expulsion of lattice water in the case of endellite $4\text{H}_2\text{O}$ and adsorbed water in the case of the

halloysite $2\text{H}_2\text{O}$ of the Fox Clay. Otherwise the curves are the same as for halloysite $2\text{H}_2\text{O}$.

Optics.—The immersion method of determining index of refraction was used on all specimens and the liquid employed was checked with an Abbé refractometer at the time the measurement was made, thus assuring a more accurate observation. The untreated Fox Clay (sample C), was found to be isotropic with an index of 1.543. In recent investigations by Alexander *et al.* (1943), the index of refraction of pure endellite $4\text{H}_2\text{O}$ was calculated as $1.49 \pm .005$. They indicate that the index of completely dehydrated endellite (halloysite $2\text{H}_2\text{O}$) may range as high as 1.556. All halloysites $2\text{H}_2\text{O}$ and endellites $4\text{H}_2\text{O}$, therefore, should fall between these extremes. The Fox Clay, with an index of 1.543, falls below the index of pure halloysite $2\text{H}_2\text{O}$. This anomaly is believed to be due to an envelope of water surrounding the halloysite grains as found by Alexander *et al.* (1943). The index of a dehydrated sample of Fox Clay was determined to be 1.556 as expected.

Electron Microscopic Observations.—Professor Tom F. Bates of Pennsylvania State University was kind enough to take an electron micrograph of the Fox Clay. The picture shows that the clay is made up of the tube-shaped particles typical of halloysite $2\text{H}_2\text{O}$.

Mineralogical Conclusions.—From the above data, it seems clear that the mineral composing the Fox Clay is halloysite $2\text{H}_2\text{O}$ and that the extra water is simply adsorbed water present interstitially and surrounding the grains. MacEwan (1947) presumes that naturally occurring halloysites may be intermediate in water content between true halloysite $2\text{H}_2\text{O}$ and true endellite $4\text{H}_2\text{O}$, and proposes a terminology based upon this concept. The results of this study support the view, however, that there are two separate and distinct minerals existing, *i. e.*, halloysite $2\text{H}_2\text{O}$ and endellite $4\text{H}_2\text{O}$, that there is not an isomorphous or continuous series between the two, and that what appears to be hydrous halloysite is nothing more than true halloysite $2\text{H}_2\text{O}$ with adsorbed water and this condition causes the index of refraction and differential thermal curves to simulate those of true endellite $4\text{H}_2\text{O}$. The nomenclature of Alexander *et al.* (1943), in using only the two terms endellite and halloysite therefore is preferred.

ORIGIN

The Fox Clay occurs between two sedimentary beds and

lenses out within the small area studied. It contains clastic quartz grains in varying amounts and no evidence of volcanic ash is observed. The clay must therefore be sedimentary in origin. It is believed that the original material was formed as endellite and was derived through the process of weathering. This was finally transported and deposited as clastic material in the clay bed along with some quartz grains. It is believed that during transportation dehydration was effected, changing the endellite to halloysite. The hydrated condition now existing is presumed to be the result of saturation at the time of deposition or through subsequent ground water activity.

ACKNOWLEDGMENTS

Appreciation is offered to the University of Utah Research Fund for supplying the differential thermal analysis equipment.

TABLE 1

Line Number	Endellite 4H ₂ O Indiana		Endellite 4H ₂ O Mehmel (1935)		Endellite 4H ₂ O Dehydrated to Halloysite Indiana		Halloysite 2H ₂ O Fresh, hydrated* Fox Clay		Halloysite 2H ₂ O Upper Silesia Nagelschmidt (1934)	
	Sample A	d I/I ₁	Sample A	d I/I ₁	Sample B	d I/I ₁	Sample C	d I/I ₁	Sample C	d I/I ₁
1	10.08	1.0	10.1	1.0	7.28	.8	7.24	.7	7.43	.6
2	4.36	.8	4.46	.8	4.40	1.0	4.40	1.0	4.44	1.0
3	3.31		3.40	.6	3.61		3.54		3.61	.8
4	2.54		2.56	.6	2.56		2.53		2.57	.8
5	2.42				2.43		2.45			
6	2.36		2.37	.5	2.36		2.31		2.36	.8
7	2.21		2.23		2.20		2.25		2.28	.2
8	2.14				2.14					
9					2.06					
10	2.01				2.02				2.01	.4
11	1.97				1.96		1.96			
12	1.90				1.90					
13	1.77				1.78		1.77			
14	1.73				1.73				1.71	
15	1.66		1.67	.5	1.67		1.67		1.63	.8
16	1.62				1.62					
17	1.46	.7	1.46	.6	1.47	.9	1.47	.8	1.47	1.0
18	1.44				1.44					
19	1.27		1.28	.6	1.27		1.27		1.29	.8
20	1.22		1.23	.4	1.22		1.22		1.23	.6

* Dehydrated Fox Clay (Sample D) shows same lines and intensities as sample C.

Intensity figure given only to three most intense lines in samples A, B, and C.

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SANDSTONE SPINDLES*

K. M. HUSSEY AND B. A. TATOR

ABSTRACT. Sandstone spindles, a peculiar feature of weathering, are found in restricted areas of the Dawson arkose (Eocene) outcrop at Corral Bluffs near Colorado Springs, Colorado. These are relatively small, spindle-shaped structures occurring in closely spaced, parallel arrangement in the surface of the exposure. They result from decementing activity by ground-water solutions which develop zones of weakness along planes of cross-bedding and jointing. Removal of the material made friable in this manner leaves the more firmly cemented portions as spindle-shaped protuberances in the face of the outcrop.

INTRODUCTION

SEVERAL years ago the attention of the writers was attracted to certain spindle-shaped features of weathering in the Dawson arkose beds (Eocene) at the site of the Corral Bluffs east of Colorado Springs, Colorado (fig. 1). These odd-shaped bodies seem to answer a description by Cotton (1942, p. 32, fig. 37) of "earth fingers" produced by wind abrasion. Detailed study of the occurrence and composition of the Colorado specimens, however, leads to the belief that the wind was not more than a contributing factor in their formation. The term "sandstone spindle" is proposed for them and the results of the study of their composition, occurrence and development are presented.

About nine miles east of Colorado Springs, Colorado, a very prominent southwest-facing escarpment, locally known as Corral Bluffs (fig. 1), has been formed by the headward erosion of a number of minor intermittent streams in the Dawson arkose.

The area has a distinctly semi-arid climate, the major part of the average annual rainfall of 14 inches being received as a series of violent local showers during the summer months. The prevailing wind direction (fig. 1) is from the southeast (U. S. Weather Bureau, 1946), changing to north during the winter months. The area in which the sandstone spindles occur is entirely devoid of soil or vegetation.

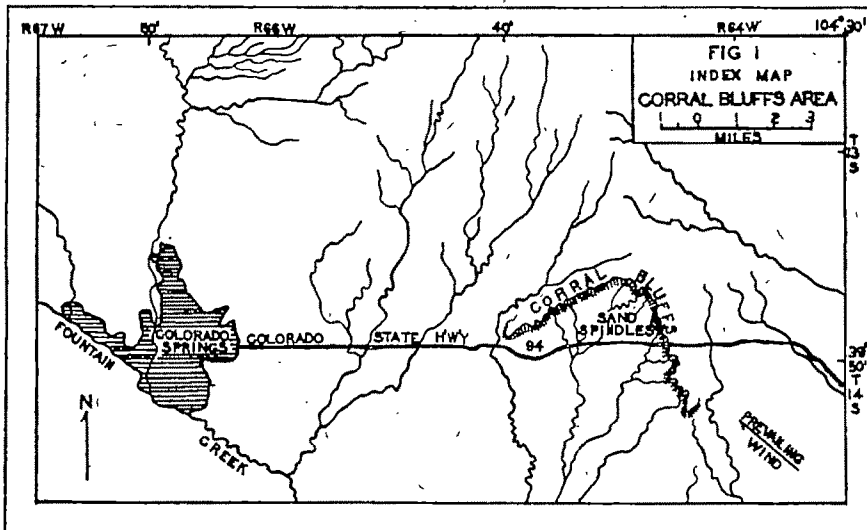
The beds exposed in the Corral Bluffs belong to the upper portion of the Dawson as described by Dane and Pierce (1936), consisting of interbedded layers and lenses of fine- to coarse-grained arkose, conglomeratic arkose, and sandy, carbonaceous

* Iowa State College and Louisiana State University Geology Camps Research Paper No. 6.

shale. The material is extremely friable, often crumbling at the touch.

The Dawson strata are essentially horizontal, though there is a regional dip of a few degrees to the southeast. The lowermost beds exposed, consisting of medium-grained, well-cemented arkose, have indeterminate thickness since they lie at the base of the escarpment. Overlying these beds is a sandy, carbonaceous shale 80 feet thick. A 15-foot layer of coarse-grained conglomeratic arkose overlies the shale, forming a bench about 100 feet above the base of the bluff. This in turn is overlain by a 6-foot layer of coarse conglomeratic arkose which, with additional beds of no importance to this writing, forms the upper part of the escarpment. All layers in this section, particularly the coarser arkoses, are strongly crossbedded. The sandstone spindles are in the upper and lowermost beds exposed.

Two sets of joints are present with relationship about normal to the bedding. These two sets, however, are not expressed with equal persistence in the same portions of the outcrop, one or the other usually being more prominent. The more pronounced set has a northwest-southeast trend; the other strikes approximately northeast-southwest. The spacing between joints varies from a few inches to several feet. The best development of the joints is in the coarser-grained



arkose beds, none being discernible in the thick shale beds in the section.

A relationship between jointing and friability of the exposed rock surface is apparent. Prominent, narrow, wall-like ridges, projecting several inches to as much as one foot above the surface of the outcrop, occupy many of the interjoint areas. These extend for as much as 8 or 10 feet laterally or vertically in the exposure. Some of them have partially developed sandstone spindles along their sides.

SANDSTONE SPINDLES

Shape and Size.—The spindles are elongate rounded cylinders composed of the same clastic material as the enclosing formation (plate 1, fig. 1). The ends are somewhat tapered in some and bluntly rounded in others, the average overall appearance being that of a spindle. The range in size is from small finger-like features about one inch in length by $\frac{1}{4}$ inch in diameter, to a maximum of 2 feet in length by over 2 inches in diameter.

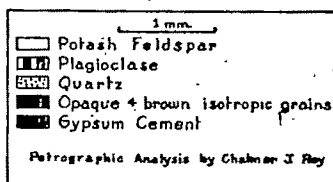


Figure 2

PLATE 1



Fig. 1. View of a west-facing slope of the Dawson arkose outcrop in Corral Bluffs. Note the horizontal and vertical alignment of the sandstone spindles.



Fig. 2. View showing the crossbedded character of the Dawson arkose. The sandstone spindles show a definite alignment with the crossbedding.

Composition.—There is no detectable compositional difference between the spindles and the enclosing formation except perhaps in degree of cementation. Microscopic study (fig. 2) of the material reveals it to be composed of approximately 25 per cent quartz, 15 per cent potash feldspar, 5 per cent plagioclase feldspar, 25 per cent unidentified opaque grains, and 30 per cent gypsum in the form of cement. The grains range from fine sand size to granule particles up to 5 mm. in diameter. The feldspar fragments comprise most of the angular to subangular grains, whereas the quartz and opaque particles are subangular to subrounded. The gypsum cementing material is crystalline, orientation of the crystals being about as shown in figure 2. Most of the grains are coated with a thin layer of iron oxide. Petrographic¹ as well as magascopic study shows this material to be concentrated in the more friable, obviously weathered areas peripheral to the spindles. The varied size and shape of the fragments allows for a close packing of the grains. Almost all of the space between the grains is occupied by the gypsum cement, which thus materially reduces the porosity and makes all but the bedding-plane and joint-plane areas relatively impermeable to water. The only difference in composition is found in the more friable zone surrounding each spindle; there the cementing material is less abundant.

Occurrence.—The sandstone spindles are present in all degrees of completeness on the surface of the outcrop. Some are lying free, completely weathered out, whereas others are not more than faint outlines. In most instances excavation of the partially exposed specimens failed to obtain a complete form. They seem to be solely the product of weathering; below the shallow weathered zone it is not possible to detect even a trace of a spindle.

These features are present only at the southeastern end of the Corral Bluffs (fig. 1) in the medium- to coarse-grained arkosic horizons of the section. Their finest development is on a westward-projecting spur in the top of the cliffed portion of the section about one-quarter mile north of State Highway 94. Poorer specimens are found, however, in the finer-grained arkose about 100 feet lower in the exposure in a creek bed a short distance from the base of the cliff. Additional, scattered, poorly formed examples occur about 50 yards north of the

¹ Petrographic analysis by C. J. Roy, Iowa State College.

above-mentioned spur in a coarse-grained, conglomeratic arkose directly overlying the spur-forming stratum.

Orientation.—The spindles have both a vertical and horizontal pattern of alignment. The vertical arrangement is associated with the joint systems mentioned earlier, whereas the horizontal pattern is directly related to the crossbedding.

These features also have the same general orientation, that is, they are roughly parallel, in any one locality. However, in the four separate places of occurrence noted, two main directions of longitudinal alignment prevail. In the coarse arkose layer outcropping on the spur top in the upper portion of the bluff, the trend is N. 75° W., being coincident in direction with the more prominent of the two joint sets mentioned earlier. In the medium-grained arkose which directly overlies the latter bed, and at a locality some 50 yards to the north, the orientation is N. 50° E. In the coarse arkose layer underlying the thick shale bed the trend is N. 75° E., whereas in the outcrop of the same layer in the creek bed a short distance west of the cliff base the orientation is N. 30° W. In the latter occurrence the spindles show a streamlining in the downstream direction, and are apparently molded at least in part by stream action.

MODE OF DEVELOPMENT

General.—A number of possibilities for the origin of the sandstone spindles have been examined by the writers. Analysis reveals that they are neither concretionary in the true sense nor of primary origin. No nucleus of foreign material, fossil or otherwise, is present in them. The texture is precisely the same in the areas between the spindles as within the features themselves, the only distinction being the better state of cementation in the latter. No trace of the spindles can be found in the unweathered arkose. Hence, they must be of secondary origin and the result of either additive or subtractive activity on the part of groundwater.

The possibility that wind abrasion has fashioned them must be excluded on two grounds. First, they occur in limited exposure protected by topography from the force of the prevailing southeasterly wind (fig. 1). Second, the orientation in two major directions within a very localized area makes it very improbable that the wind could etch the exposed rock surface in two different directions at the same time. Furthermore, lack

of occurrence of the forms in strata of widespread textural similarity, in many localities exposed to the full force of the prevailing wind, would seem to eliminate this agency as a primary cause of their development.

Similar-appearing features have been described by Barbour (1901) in outcrops of the Arikaree formation (Miocene) in Nebraska and South Dakota. However, he found that the controlling factor was a radiating growth of secondary calcite which, as a cementing agent, created true concretions. Petrographic analysis of the sandstone spindles proves that no such controlling secondary mineral growth is present.

Influence of Crossbedding.—The exposure containing the finest developed examples is strongly crossbedded. A decided alignment of the spindles with the crossbedding is apparent (plate 1, fig. 2). They occur in the thinly layered units between the bedding planes. It would appear then that the planes of contact between adjacent units of the crossbedding provide greater freedom for the movement of groundwater solutions which act as decementing agents. Under such circumstance the removal of cement would be an inward-progressing process in each of the crossbedded units (fig. 3). Thus the spindle alignment with these units in horizontal dimensions is explainable on the basis that these are areas from which the cement has not been removed.

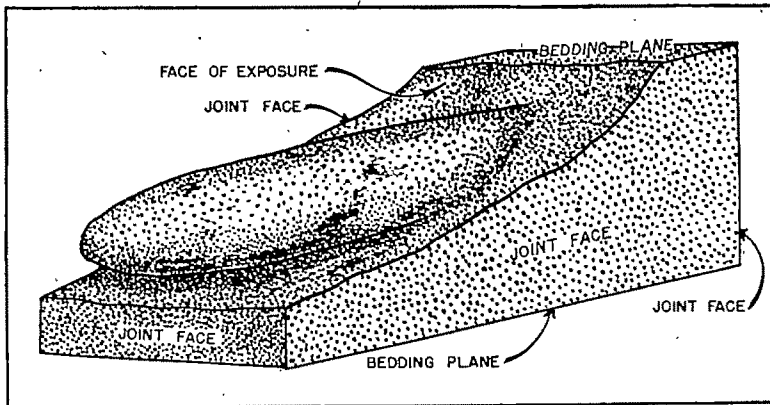


Fig. 3. Idealized diagram of a trapezohedral rock unit showing the means of development of a sandstone spindle by decementation. The joint faces and bedding planes provide ease of ingress for solutions which progress inward. The spindle is a residual core which still retains its cement. Differential weathering then leaves the feature as a projection from the face of the exposure.

Influence of Joints.—In the vertical dimension the two major joint systems noted earlier are the controlling factor in the location and the spacing of the spindles; the greater prominence of one set of joints determines the direction of elongation. The decementing activity of groundwater solutions along the joints has developed greater friability in zones roughly perpendicular to the crossbedding. Thus the sandstone spindle may be thought of as occupying the central portion of a trapezohedron, the length, breadth, and height of which is determined by the spacing of the joints and the thickness of the units of crossbedding. The trapezohedron is affected from all sides by solutions working inward from the surrounding zones of freer movement (fig. 3). Iron staining of the peripheral portions of the spindles tends to support this view, particularly since the stained areas are also more friable than the central portions. The decementing action undoubtedly involves a removal of the gypsum cement by percolating ground water. This leaves a zone of practically uncemented grains on five sides of the trapezohedron.

The projecting nature of the spindles in the exposure is the result of differential weathering. The more friable zones are worn back more rapidly than the relatively better-cemented areas; this action involves removal of the loosened clastic fragments from the surface of the exposure by rainwater and wind. The slower weathering of the more coherent centers of the trapezohedral units allows them to remain as spindle-shaped projections in the face of the exposure.

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COMMUNICATION

A *Geological Map of British Columbia* recently issued by the Geological Survey of Canada, with scale of one inch to twenty miles, illustrates the energy of a Survey which is responsible for a scientific treatment of 4,000,000 square miles or one-twelfth of the world's dry land. British Columbia alone is one-tenth of the Dominion. Although little more than one-fourth of this map bears designating colors for the exposed formations, it is eloquent of the inestimable amount of foot-slogging, perspiration on hob-nails, during the 75 years since George Mercer Dawson began his remarkable reconnaissance. A wild, rugged country, where rock outcrops are much diminished by almost continuous forest cover and where there is limited access by railways, dirt roads, and even horse-trails, is this scene of hard labor. Yet the devoted workers in the province have shown the intriguing quality of the geology of the 95,000 square miles actually colored—a total area six times that of the more accessible Switzerland.

On the present occasion only one outstanding feature of the map will be emphasized. It bears no color representing any definitely Archean or "Archeozoic" group of formations, and this in spite of gigantic upturnings and upthrustings of thick masses of the earth's crust. The oldest formations of the legend include the Purcell series and the unconformably overlying Windermere series, both referred to the "Proterozoic" and thus to be regarded as analogues of the Beltian or Algonkian. In contrast Dawson regarded the "Shuswap complex" of granites, gneisses, schists, pegmatites, aplites, marbles, and greenstones, occupying considerable areas west of the Selkirk Range, as a true Archean terrane from which were chiefly derived the main bulk of the voluminous Late pre-Cambrian and Cambrian clastic sediments of the province. The International boundary from the Great Plains to the Pacific nowhere crosses a typical and proved Archean assemblage, nor has any been found in Vancouver Island or the Queen Charlotte Islands. On the other hand, the present writer's 1911-1912 reconnaissance along the main line of the Canadian Pacific Railway from Kamloops to Golden appeared to corroborate Dawson's reference of the "Shuswap complex" to the Archean. The new evidence was derived near Albert Canyon station, where to the west a broad band of Shuswap rocks makes sharp contact with a thick mass of Beltian-Cambrian clastics extending all the way to the Great Plains. East of that contact the writer, after prolonged search, failed to find a single pegmatite or aplite dike or sill cutting the basal Beltian beds. This fact, coupled with microscopic study of the basal quartzite, suggested that here is a major unconformity (more specifically an arkose unconformity) between the two ter-

ranes. No other such evidence by unconformity seems to have been published.

After 1912 S. J. Schofield and other members of the Survey staff showed that the late-Mesozoic batholithic invasions of the province developed granite-gneiss-pegmatite-aplite complexes like that of the Shuswap terrane west of Albert Canyon station. In Part A of the Survey's Summary Report for 1928 H. C. Gunning reported his discovery that the Beltian sediments a few miles east of Albert Canyon station are cut by dikes of both pegmatite and aplite, and that only a short distance to the south is an outlier of a large late-Mesozoic batholith clearly intrusive into the Beltian series. He therefore concluded that the Albert Canyon contact is better explained as intrusive rather than as one of unconformity. To the present writer this deduction was long uncertain, since he saw no reason against assuming two epochs of granite-pegmatite-aplite eruption, one pre-Beltian and the other late Mesozoic. However, a recent study of Gunning's field data (further detailed in a personal letter of 1924 and also in his 1929 report on the "Big Bend Map-area") and of the relevant memoirs by other members of the Survey has led to the conclusion that, with a high degree of probability, Gunning was right in his judgment, and that all these explorations along the Cordilleran strike show the Albert Canyon "unconformity" to be illusory: that the adjacent "Shuswap" rocks are not to be referred to the Archean.

Sharing that opinion, the Survey men are conscious of a mystery: what was the chief dry-land source of the Proterozoic and Cambrian, clastic sediments of British Columbia? The same problem in the paleogeography of pre-Ordovician time is far from solution in the Cordilleran belts of both Yukon Territory on the north and the United States on the south.

It has been suggested from field evidence that most of those ancient sediments were not derived from the Archean shield of eastern Canada but did come from a broad terrane ranging along the Pacific side of the most westerly islands from Alaska to California. Such a land-mass, presumably sialic and capable of supplying the enormous volumes of quartzites and metargillites in the Beltian geosynclinal prisms, was imagined by C. Schuchert and named by him "Cascadia." A. J. Eardley (*Am. Assoc. Petroleum Geologists Bull.*, 1949, vol. 88) accepts the same general idea but prefers to describe the parent terrane as a "Volcanic Belt." Neither of these conceptions of the parent terrane has been discussed in relation to the principle of isostasy. Neither terrane is now visible. The maps of Schuchert and Eardley show the place of the vanished terrane to have been largely taken by Pacific water approaching 12,000 feet in depth. Yet there is reason to believe that gravity is nearly normal along the same belt, now

offshore, and good reason for doubt that the sunken terrane could have had its density increased so much as to ensure near-isostasy after the supposed subsidence.

If, then, the bulk of the Proterozoic and younger clastic sediments of British Columbia be assumed to have "come from the west"—from a broad long-lived land of Archean rock situated west of the present outermost shore of the Pacific—some additional speculation is in order. Is it too fantastic to guess that that parent terrane became buried under North America when the western part of our existing continent slid over or was thrust over the simatic Pacific sector of the earth's crust?

REGINALD A. DALY

REVIEWS

Outlines of Biochemistry; by the late ROSS AIKEN GORTNER. Revised by SAMUEL I. ARONOVSKY, PAUL D. BOYER, DAVID R. BRIGGS, HENRY B. BULL, GEORGE O. BURR, WILLIAM F. GEDDES, ROSS A. GORTNER, JR., WILLIS A. GORTNER, W. M. SANDSTROM, and J. J. WILLAMAN; 3rd ed., edited by ROSS AIKEN GORTNER. Pp. xv, 1078; 125 figs. New York, 1949 (John Wiley & Sons, Inc., \$7.50).—

This second revision of Gortner's Outline is a timely contribution to the field of biochemistry in which so many dramatic advances have been made during the past ten years. The new edition results from the efforts of the late Ross Gortner's two sons, Ross A. Gortner, Jr., and Willis A. Gortner, aided by a highly competent staff of eight collaborators. All of the latter were in some way associated in biochemistry with Gortner, Sr.

The book is unique in presenting, in a very comprehensive fashion, the organic chemistry and physical chemistry upon which biological phenomena are based. However, little attempt has been made, as in previous editions, to correlate the theory with the bulk of the descriptive material. No attempt is made to cover practical or clinical applications of biochemistry except for occasional illustrative purposes; for this reason, the approach is not of primary interest to a medical student. Rather, the book will be eminently useful to anyone desiring to keep abreast of recent developments in biochemistry through a rapid survey of the field.

In the new edition, there are revisions to nearly all the chapters, especially those on vitamins, protein metabolism and polysaccharides, and new sections on carbohydrate metabolism, lipid metabolism and protein denaturation have been added. The sections on colloids and carbohydrates are especially well organized and clearly written.

As was the case with previous editions, the book should be widely read and enjoyed.

HARRY H. WASSERMAN

Selenium. Its geological occurrence and its biological effects in relation to botany, chemistry, agriculture, nutrition and medicine; by SAM F. TRELEASE and ORVILLE A. BEATH. Pp. x, 292; 66 figs. New York, 1949 (Published by the authors, Box 42, Schermerhorn Hall, Columbia University, \$5.50).—Selenium is almost unique among the chemical elements occurring in toxic concentrations in the biosphere. It is accumulated by certain plants, notably of the genera *Astragalus*, *Xylorhiza* and *Oenopsis*, which if eaten continuously by livestock cause a serious, usually fatal, condition known as blind staggers. Selenium may also enter to wheat and grasses from richly seleniferous soils. When these plants are eaten the selenium produces a different pathological state, the so-called alkali disease; a condition comparable to alkali disease probably exists in

man. Trelease and Beath have produced an admirable monograph, of equal interest to the stockman and the geochemist, on the selenium cycle in nature in both its theoretical and applied aspects. The whole of the geochemical and botanical literature is considered. It is evident that the selenium problem is sufficiently well understood to enable intelligent control to be undertaken in the selenium belt that stretches north from New Mexico through Wyoming into Canada. There, however, is still an enormous amount of work to be done on the purely scientific aspects of the problem. The explanations of the localized occurrence of seleniferous sediments in various Cretaceous formations are unsatisfactory. Almost nothing is known of seleniferous sediments, soils, and plants outside North America. The physiology of the apparent need for selenium by certain species of *Astragalus* requires further investigation, and the study of the organic chemistry of the selenium present in accumulator plants has only just begun. If the authors succeed in stimulating further work on these problems they will be intellectually rewarded; since they have evidently had to take considerable risk in producing the book themselves, it is also to be hoped that they will be financially rewarded by many investigators purchasing their work.

G. EVELYN HUTCHINSON

Annual Reports on the Progress of Chemistry for 1948 (Volume 45); issued by THE CHEMICAL SOCIETY. Pp. 879. London, 1949 (£1.5.0).—This volume is written by 22 experts. It summarizes the progress in certain fields of chemistry during previous years; in some cases since earlier reviews. There are 21 articles collected under the headings of general and physical, inorganic, organic, and analytical chemistry and biochemistry. As one comes to expect of the Reports the writing is clear, scholarly, yet on the whole lively, so that reading is a pleasure. Workers in the field of the earth sciences might find particularly valuable the coherent view of chemical reactions induced by ionizing radiations, by F. S. Dainton. In the biochemistry section there is a thorough review of partition chromatography by A. J. P. Martin. The analytical section contains reviews of analytical emission spectrography; flame photometry; volumetric analysis; and analysis of sea water.

HAROLD G. CASSIDY

Artificial Radioactivity; by P. B. MOON. Pp. 102. New York, 1949 (Cambridge University Press, \$2.50).—This is an authoritative monograph on its subject matter. It presents an outline of the main phenomena and techniques of radioactivity, focussing its emphasis upon recent developments in the study of light- and medium-weight radioactive nuclei. Their variety is so great that com-

plete coverage of the field in so small a volume is impossible. But the book is most useful because of the significance of the examples chosen for treatment and because of its references to the current literature. It provides a survey rather than an explanatory text.

HENRY MARGENAU

Excited States of Nuclei; by S. DEVONS. Pp. 152. New York, 1949 (Cambridge University Press, \$2.50).—Nuclear spectroscopy is rapidly becoming a subject of enormous complexity, largely unrelieved at present by the attempts of theorists to unravel its complications. Accordingly, the monograph under review is mainly an empirical account of a vast body of information, collected in 4 chapters which deal, successively, with excitation of bound nuclear states, excitation of virtual states, radiative transitions and interpretations. All discussions are up to date. And while the author confers his principal emphasis upon experimental methods, he nevertheless succeeds in providing as complete and satisfactory a picture of the theoretical situation as skill and good judgment can supply.

HENRY MARGENAU

A General Kinetic Theory of Liquids; by M. BORN and H. S. GREEN. Pp. 98. New York, 1950 (Cambridge University Press, \$2.25).—Six important papers, published by the authors in the Proceedings of the Royal Society A, are collected and issued in book form. They deal with general questions of the kinetic theory, the quantum mechanics of fluids, and culminate in an application of the new theory to liquid helium.

HENRY MARGENAU

Introduction to Theoretical and Experimental Optics; by JOSEPH VALASEK. Pp. x, 454. New York, 1949, (John Wiley & Sons, Inc., \$6.50). This is not only a general text covering all the usual topics in optics and spectroscopy, but it will also serve excellently as a fairly elementary and up-to-date reference book in applied optics and optical engineering. Only a course in general physics and one in the calculus are assumed as background. The book is divided into four parts: geometrical optics, physical optics, radiation and spectra, and experimental optics. There are twenty-four experiments, including three with x-rays, plus a section on the photographic process, in this last part. X-rays, photographic optics and ophthalmic lenses, three specialties of the author, are treated in more detail than usual in optics texts.

There are a number of problems applying the theory at the end of each chapter. Although the consideration of topics in modern optics seems complete, some developments such as colorimetry are treated in rather cursory fashion. References are always included,

however, and the discussions are accurate as far as they go. This book is highly recommended as an optics text at the intermediate level and as a useful reference source on optical problems encountered by specialists in other fields.

W. W. WATSON

Vacuum Equipment and Techniques; by A. GUTHRIE and R. K. WAKERLING, editors. Div. 1—Vol. 1 of National Nuclear Energy Series. Pp. xvii, 264. New York, 1949 (McGraw-Hill Book Co., Inc., \$2.50). This volume is one of about sixty now being published in the National Nuclear Energy Series as a result of the huge amount of scientific and technical research and development done under the auspices of the Manhattan District during the war. It gives the observations made in the high-vacuum program at the University of California Radiation Laboratory. The large-scale equipment built according to the designs resulting from this research program was an important contribution to the success of the electromagnetic separation plants at Oak Ridge.

In a rather lengthy Chapter 1 R. Loevinger gives an excellent account of those parts of the kinetic theory of gases that are useful in modern vacuum practice. Another feature improving this as a reference work is a set of appendices giving all the necessary formulas, conversion factors, and properties of materials. W. E. Bush has written two chapters: Elements of the Vacuum System, and Vacuum Materials and Equipment. There is a chapter on Vacuum Gauges by K. M. Simpson. The final chapter on Leak-detection Instruments and Techniques includes among other topics complete descriptions of the vacuum analyzer and the helium leak detector developed for use in this project.

Now we have large and important industrial processes and whole new industries based on these vacuum techniques! All experimental scientists and engineers who must produce a high vacuum will find this a valuable reference volume. It is a bargain, too, considering the present high prices of books.

W. W. WATSON

Seismicity of the Earth and Associated Phenomena; by B. GUTENBERG and C. F. RICHTER. Pp. x, 273; 84 figs. Princeton, New Jersey, 1949 (Princeton University Press, \$10.00).—The title of this volume has appeared on several papers and abstracts published by the same authors within the past ten years. Their matured studies have led to results of large proportions and importance, and these results are now embodied in a book that will be welcomed by students of earth science. Considerably more than half of the pages, which measure 7.5 x 10.7 inches, are devoted to organized tabulation of shocks, numbering many hundreds, for which significant data are available. This part of the book is in

itself a highly valuable reference work. The first 100 pages are occupied with explanation and discussion, including not only text but also helpful maps and diagrams. A list of references to literature, alphabetized according to authors, requires 18 double-column pages. There are two indexes, one listing authors of reference literature, the other subjects treated in the present volume.

Materials and methods used in the study are clearly stated and explained in introductory sections. Magnitudes of earthquakes included range up to a maximum of $8\frac{1}{2}$, on the scale developed from the suggestion by Richter, in classifying shallow shocks in southern California, that the number to express the magnitude of a shock be "the logarithm of the maximum trace amplitude expressed in thousandths of a millimeter with which the standard short-period torsion seismometer would register that earthquake at an epicentral distance of 100 kilometers." Later elaboration of the scale, including development of a nomogram, makes it applicable to all earthquakes that have been well recorded, whatever the type of instrument used. Magnitudes are correlated with amplitudes and periods of *P*, *PP*, and *S* in the records; this makes possible the inclusion of deep shocks, for which surface waves are small or practically absent. For the deep shocks, however, certain assumptions are involved regarding propagation of seismic energy in the interior of the earth, and accordingly some error in computed magnitudes is recognized.

Shocks are defined as shallow if depth of focus does not exceed 60 km.; intermediate if they fall within the limits 70 to 300 km.; and deep if the focus is below 300 km. By magnitude all shocks fall into five classes designated *a*, *b*, *c*, *d*, and *e*; those in *a* have the range $7\frac{3}{4}$ - $8\frac{1}{2}$, those in *e* are below 5.3, and shocks in the other three categories have intermediate limits. For deep shocks the quality of determination ranges from *A* (very accurate) to *D* (poor); even for those classed as *A* the limits of error are: for location of epicenter 1° , for origin time $\pm$ sec., for depth 30 km.

For convenience in reference the surface of the earth is divided into regions, boundaries of which are shown by an index map on modified Mollweide projection. Other maps, on the same projection, show: (1) shallow earthquakes of class *a* for the period 1904-1946, and of class *b* for 1918-1946; and (2) intermediate and deep-focus earthquakes, classes *a* and *b*, for 1904-1946. Of particular interest is the highly seismic circum-Pacific belt, which includes "a large majority of shallow shocks, a still larger fraction of intermediate shocks, and all the deep shocks in the restricted sense." Distribution of shocks in these three classes, in relation to island arcs and to the west coast of South America, commands attention of all students of tectonics. The vista of possibilities that lie in this kind of geo-

physical study is made more impressive by maps, chiefly of the East Indies and neighboring units, that depict earthquake data, gravity anomalies, volcanoes, and ocean depths. An impressive sketch map (Fig. 33) represents the "Pacific stable mass" framed by the belts of shallow, intermediate, and deep-focus earthquakes. Figure 34 represents each of the "continental stable masses" in relation to seismic belts.

Data from each major region of the earth are presented in considerable detail. General discussion is limited in scope, but brief sections deal with views on the constitution of the earth and on the mechanism of crustal movements. The largest contribution of the book lies in its presentation of basic data. In this respect it marks a significant advance in the pooling of information by the several disciplines engaged in the attack on fundamental problems of the earth's crust.

CHESTER R. LONGWELL

Lehrbuch der Paläozoologie; by OSKAR KUHN. Pp. v, 326; 244 figs. Stuttgart, 1949 (E. Schweizerbart'sche Verlagsbuchhandlung, 28 marks unbound, 30 marks [\$7.20] bound).—At first sight this handsome and richly illustrated new textbook will fascinate any paleontologist. With closer examination misgivings will arise and these may finally give way to dismay.

Kuhn belongs to the school of idealistic morphology of Naef and others, a school that is pre-evolutionary in source and outlook, as Kuhn recognizes, although this is denied by some other adherents. On principle, he rigidly orients this text around exposition of the "Urbild" ("archetype" of earlier days, "morphotype" of some modern students). With the single exception that he usually gives the geological age of the groups mentioned, the treatment is confined to diagnosis. The limitation is so stringent that it excludes not only faunal succession, phylogeny, paleoecology, paleobiology, or any mention of evolutionary, geological, or, indeed, paleontological principles, but also morphology itself. There is no systematic or, even on an elementary level, adequate exposition of the structure of any group of fossils.

The text is, then, essentially a series of summary diagnoses of each phylum ("Kreis") known as fossils and of lesser groups, usually carried down to orders, with some sporadic notice of particular genera but practically no mention of families or other intermediate categories. These diagnoses, as such, are generally adequate and useful. It is inevitable in so extensive a compilation that errors of detail have crept in, although they seem in some places to be more numerous than is strictly necessary.

The illustrative material is remarkably extensive and makes a useful collection of figures. Many of the 244 numbered figures are

multiple, so that the number of separate illustrations may be over a thousand. Yet even this truly outstanding feature of the book must be viewed with some reservations, because the figures are very uneven in quality and are commonly drawn from secondary sources, with reference to the true source omitted or incorrect. Such a criticism requires some documentation. Figure 218, captioned "Skelett eines oberjurassischen Stegosauriers . . . Nach ROMER," is a direct, although reduced and somewhat blurred, copy of a figure published by Barnum Brown in 1908 and not reproduced in any work by Romer known to this reviewer. Moreover, as was clearly stated by Brown, the animal is late Cretaceous, not late Jurassic, in age and it is an ankylosaur, not a stegosaur. The single example must suffice here, but it is not an isolated instance.

A book should be judged within the framework of its author's own aims. This book is intended as a text on diagnosis of major groups of fossil animals for German-speaking students and as such it is reasonably successful, with certain reservations as already suggested. Using due caution, American paleontologists may find it occasionally helpful as a broad work of organization and reference.

G. G. SIMPSON

Die Festigkeitserscheinungen der Kristalle; by H. TERTSCH. Pp. vii, 810; 219 figs. Vienna, 1949 (Springer Verlag, \$9.60). Commenting that mineralogists treat various branches of physical crystallography with varying degrees of thoroughness, Tertsch sets out in this book to help remedy the unbalance by presenting a careful review of certain solid properties of crystals. He covers four main subjects, namely cleavage (46 pp.), plasticity (214 pp.), hardness (86 pp.), and percussion and pressure figures (25 pp.). Each of these subjects is introduced by an historical and general section, followed by appropriate sections on qualitative and quantitative observations, and finally by theoretical interpretations.

No attempt is made to introduce new material, but rather to collect and review what is already available; the result is exceedingly satisfactory. As stated by Tertsch himself, summaries of knowledge usually introduce many new questions not previously considered; this book is no exception. To review a problem intelligently is nearly always the first step toward a further, successful attack upon it.

As a text or as a reference, this book is lucid and thorough enough to serve both students and research workers. The 12-page index, and the 15-page bibliography (317 references) are well arranged to promote both purposes. The cross-indexing of secondary authors in the bibliography is particularly commended. The whole book is a good job, well done.

HORACE WINCHELL

Studies on Triassic Fishes, II. Australosomus and Birgeria; by EIGIL NIELSEN. Meddelelser om Grønland, Band 146, nr. 1; 82 figs., 20 plates. København, 1949 (25,00 Kr.).—The second portion of Dr. Nielsen's monograph of the Triassic fishes collected by the Danish East Greenland Expeditions under Dr. Lauge Koch between 1932 and 1938 deals with two genera of somewhat advanced chondrosteian fishes from the Eotriassic, mainly of the Kap Stosch area. *Australosomus kochi* (Stensiö) was a fish averaging 12 to 15 cm. long belonging to the Pholidopleuridae, a family derived from the primitive paleonisciform fishes of the Paleozoic which had evolved toward, but never attained holostean structure. *Birgeria groenlandica* Stensiö, known from both small (9-21 cm.) and larger (53-84 cm.) specimens, was a predaceous fish with an enormously enlarged mouth and a body almost naked of scales, and is close to the ancestry of the living paddle fish and sturgeons. Nielsen exhaustively describes every part of the skeletal anatomy of these fishes on the basis of 235 specimens of the former and 109 of the latter. The skull and endocranial cavities of *Australosomus* are described and figured from wax models constructed from serial sections ground at intervals of 100 (in critical regions 50) microns.

In passing, a number of general remarks are made concerning bony fish evolution. Nielsen repeatedly points out resemblances between primitive Actinopterygians and Acanthodians, and suggests the origin of the bony fishes from the latter group. Westoll's hypothesis that the position of the pectoral fin in bony fish shifted from horizontal to vertical in correlation with loss of the heterocercal tail is questioned, as both *Australosomus* (with horizontal pectoral and nearly homocercal tail) and *Birgeria* (with vertical pectoral and unreduced heterocercal caudal) present contrary combinations.

The question of priority of *Xenesthes* Jordan over *Birgeria* Stensiö is passed over in silence; this is a matter, however, for action by the International Commission on Zoological Nomenclature rather than continued individual discussion.

Dr. Nielsen is furnishing extremely useful basic data for the phylogeny of the bony fishes and a valuable set of types for anatomical comparison. The excellent plates, numerous well labeled figures, orderly presentation, and full summaries so characteristic of publications of the Scandinavian paleontologists leave little to be desired. It is to be hoped that further reports on this fauna will appear at shorter intervals than intervened between parts I and II.

JOSEPH T. GREGORY

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American Journal of Science

NOVEMBER 1950

LATE PRE-CAMBRIAN OR LOWER CAMBRIAN FORMATIONS IN CENTRAL VIRGINIA

ROBERT O. BLOOMER

ABSTRACT. It is generally believed that there is a significant hiatus between the Catoctin formation and the Chilhowee series. The Catoctin and the concordantly underlying Lynchburg and Swift Run formations are defined as late pre-Cambrian and the Chilhowee as Lower Cambrian. Although the age classification may be correct, there is evidence of a continuous sequence from the base of the Lynchburg into the Chilhowee. This relationship may appear to be refuted where the Chilhowee rests with conspicuous unconformity upon a granitized complex definitely older than late pre-Cambrian. However, this unconformity is an inclined surface that cuts across formation boundaries. The Lynchburg and Catoctin overlap this surface from east to west. Consequently, the absence or restricted thickness of the Catoctin beneath the Chilhowee in certain sections is not due to an interval of erosion between the two formations, but to the location of the sections with respect to the margin of the overlap.

In places, there appears to be a complete section between the Catoctin in the Blue Ridge and the Wissahickon in the Piedmont of central Virginia. No continuous faults, including the Martic overthrust, have been identified despite a painstaking search. In other words, the Catoctin is not everywhere separated from the Wissahickon or the Lynchburg from the Wissahickon by faults.

These relations indicate the presence of a vast thickness of metasedimentary rocks of predominantly terrigenous character interrupted by several thousand feet of greenstone southeast of the Blue Ridge. The metasedimentary rocks above the greenstone are in the Wissahickon formation and those below the greenstone are in the Lynchburg formation. The Wissahickon, therefore, is Paleozoic in age and at least partly equivalent to the Lower Cambrian Chilhowee group of the Appalachian geosyncline. The Blue Ridge is generally recognized as the southeastern margin of this geosyncline. If the Wissahickon is Paleozoic in age as here interpreted, the geosyncline is actually much more extensive and the complex northwest of the Blue Ridge is a foreland trough.

INTRODUCTION

DURING all or part of the past ten summers, the writer has made a detailed study of the Blue Ridge province between James River and Rockfish Gap in central Virginia. Two quadrangles have been mapped on a scale of approxi-

mately one inch to the mile and other areas studied. The work has extended a short distance into the Valley and Ridge province to the northwest and into the Piedmont province to the southeast.

Before the geology of the Blue Ridge and Piedmont provinces can be integrated with the better-known geology of the Valley and Ridge province, the stratigraphic relations of certain formations must be established. One such formation is the Catoctin greenstone and another is the Lynchburg formation.

Bloomer and Bloomer (1947) conclude that the Catoctin and the underlying Swift Run (Oronoco) are older than the Lower Cambrian Chilhowee group, but Cambrian in age. Stose and Stose (1949, pp. 298-299) and King (1949, pp. 636-638) have defined the Catoctin as older than the Chilhowee group, but late pre-Cambrian in age. Excepting the age, there seems to be more agreement than disagreement regarding the stratigraphic relations of the Catoctin formation.

An effort is here made to interpret the relationship of the Catoctin to the overlying Chilhowee group and to the underlying Swift Run and Lynchburg formations. When the relations of these formations are firmly established the paleogeography may be better understood and the location of the boundary at the base of the Cambrian might be more successfully argued.

TABLE I
SEQUENCE OF FORMATIONS IN THE BLUE RIDGE REGION
OF VIRGINIA

Southwest of Roanoke		Central Virginia	Northeast of Rockfish Gap	
Chilhowee Group	Erwin	Erwin-Antietam	Antietam	
	Hampton	Hampton-Harpers	Harpers	CAMBRIAN
	Unicoi	Unicoi	Weyerdon Loudoun	
		volcanics	volcanics	?
		Swift Run (Oronoco)	Catoctin	
	Lynchburg?	Lynchburg	Swift Run Lynchburg	Pre-C
		Injection Complex "Gneissized Complex"	Injection Complex	

LOWER CAMBRIAN FORMATION NAMES

As shown by table 1, one set of names is used for the Cambrian formations southwest of Roanoke and another for the Cambrian formations northeast of Roanoke (Butts, 1940, pp. 26-40). Inasmuch as there is little difference in lithology, stratigraphy, or thickness from southwest of Roanoke at least to Tye River Gap, 64 miles northeast of Roanoke (fig. 1), the present usage of two sets of names for the lower Cambrian formations seems somewhat arbitrary. Indeed, it is confusing. In central Virginia, for example, the Weverton formation is represented by a coarse-grained quartzose facies that forms lenticular bodies, from about 3 inches to 25 feet thick and a few hundred feet long, at irregular intervals in an arkosic sandstone facies that resembles typical Loudoun. The Wever-

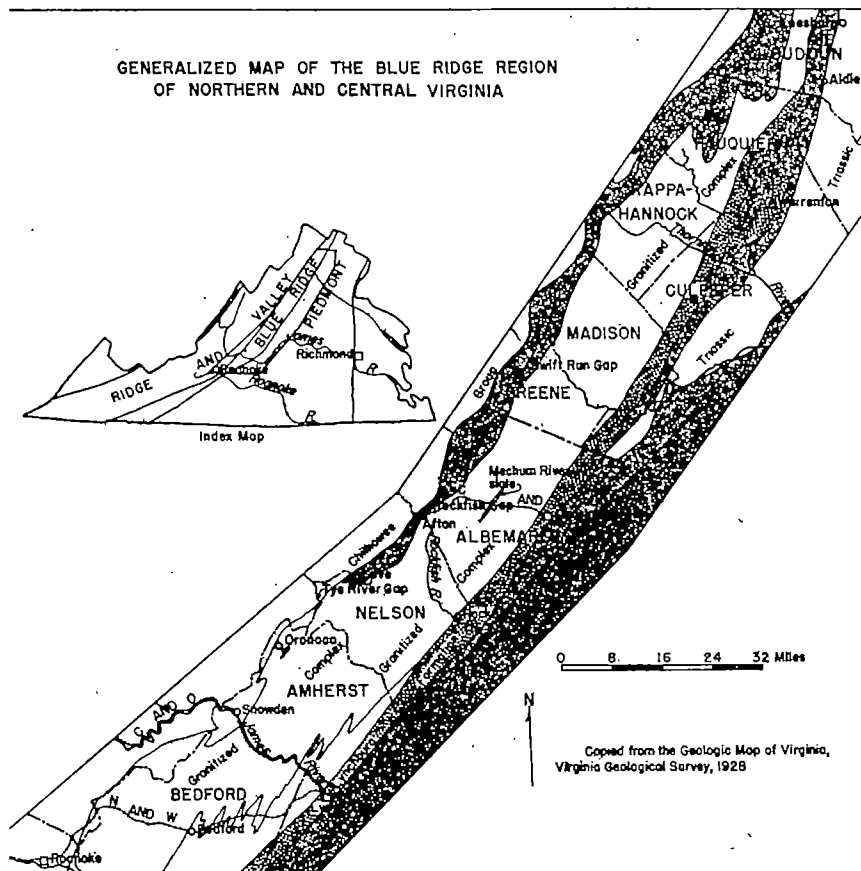


FIGURE 1

ton, consequently, is not a well-defined lithologic unit differentiable as a formation in central Virginia unless all the rocks above the graywacke conglomerates and volcanics at the base of the Chilhowee are Weverton. If this is true, the Loudoun is only about 100 feet or less thick. Furthermore, the quartzose pebble conglomerates characteristic of the Weverton are contained in the basal graywacke conglomerate. Keith (1894, p. 326) refers to places at the north and south ends of Catoctin mountain in northern Virginia where the Weverton is underlain by only a few feet of Loudoun. Although this restriction in the thickness of the Loudoun may be due to overlap or erosion, neither of these explanations seems plausible. The total thickness of the formations appears to be comparatively unchanged so that the presumption is that the Weverton is extended downward at the expense of the Loudoun. Consequently, there seems to be some question of the status of the Weverton even in northern Virginia. Is the Weverton a well-defined, mappable formation or a facies of variable stratigraphic range?

In central Virginia, if the northeastern set of names is used, the Weverton has to be omitted. This might imply an unconformity, whereas, in fact, the absence of the formation is due to facies gradation.

The names Loudoun, Weverton, Harpers, and Antietam were assigned before the names Unicoi, Hampton, and Erwin. The Unicoi is approximately equivalent to the combined Loudoun and Weverton (King, 1949, pp. 522-523). Where the Weverton is not differentiated, Unicoi should be the preferred name for the formation. Thus, the Unicoi is identified at least as far as Tye River Gap, 64 miles northeast of Roanoke. Northeast from Tye River Gap for 25 miles or more there are several overthrust faults in Chilhowee rocks (fig. 2). These rocks are mylonitized and the stratigraphic section is fragmentary so that the formations are incomplete and hardly differentiable. It has not been possible in this portion of the Blue Ridge to trace the Unicoi northeastward into well-defined Loudoun and Weverton.

The Hampton formation is similar in lithology, thickness, and stratigraphy to the Harpers formation. These formations appear to be equivalent and the dual classification seems unnecessary. The name Harpers is older than the name Hampton and should have precedence. Similarly, the earlier-named

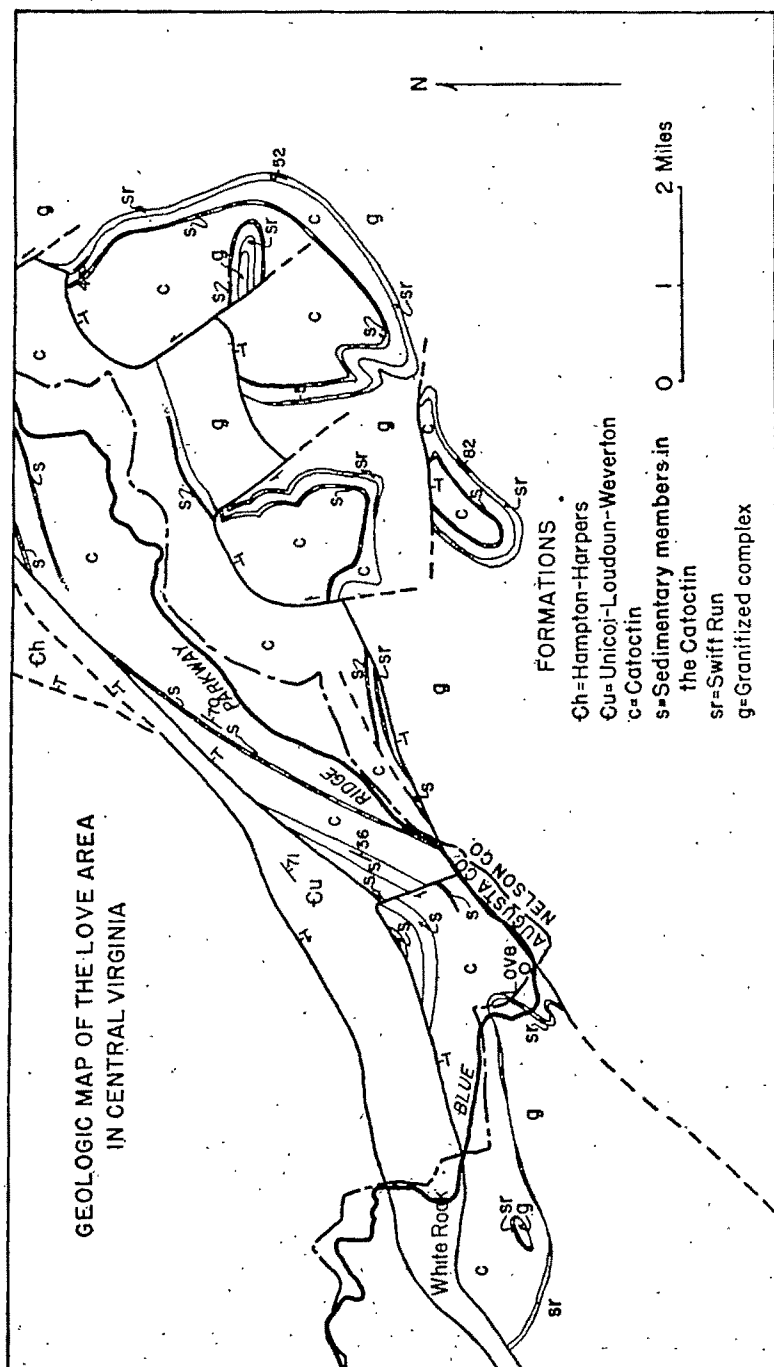


FIGURE 2

Antietam is equivalent to the Erwin and should have precedence. The Shady and Rome formations, on the other hand, were named before their northeastern equivalents, the Tomstown and Waynesboro.

On the basis of priority of names, approximate equivalence, and lithology, the sequence of formations in the Lower Cambrian of the Blue Ridge at least as far northeast as Tye River Gap should be :

Rome	
Shady	
Antietam	} Chilhowee group
Harpers	
Unicoi	

This usage of names is contrary to convention. On the other hand, the Roanoke boundary seems to be arbitrary and unrecognizable in the stratigraphy. Perhaps the use of certain names from two well-established sets is objectionable. For this reason, the names Unicoi, Hampton, and Erwin, contrary to rule, have been used in central Virginia (Bloomer and Bloomer, 1947, pp. 96-97, 103-106).

GRANITIZED COMPLEX

The stratified rocks of the Blue Ridge and northwest margin of the Piedmont provinces unconformably overlie a complex of gneisses and granitoid rocks. This complex, in central Virginia, is 10 to 20 miles wide between the Lynchburg gneiss on the southeast and the Swift Run (Oronoco), Catoctin, or Unicoi formations on the northwest. It consists of three widespread facies including the Lovingsston gneiss, Marshall granite, and hypersthene granodiorite delineated on the Geologic Map of Virginia (Virginia Geol. Survey, 1928). The Lovingsston gneiss comprises about two-thirds of the complex. It forms an irregular, elongate mass about 12 miles wide at Rockfish River and 150 miles long from Roanoke River on the southwest to Thornton River on the northeast (fig.1). Marshall granite forms an irregular mass about 2 to 5 miles wide along the northwestern margin of the Lovingsston. Hypersthene granodiorite forms a mass as much as 8 miles wide northwest of the Marshall. The granodiorite is unconformably overlain by the Swift Run (Oronoco), Catoctin, or Unicoi formation in the Blue Ridge. Numerous comparatively small bodies of granodi-

orite are included within the Lovingston gneiss. Marshall granite underlies low hilly country between the Blue Ridge and a belt of outlying, intricately dissected ridges formed from the Lovingston.

The hypersthene granodiorite is a medium- to coarse-grained, locally porphyritic, granitoid rock. The rock is predominantly massive, but a relic foliation formed by chlorite appears in places. There is insufficient concentration of the micaceous mineral to produce well-defined folia. Potash feldspar, plagioclase, blue and smoky quartz, and chlorite are the most persistent essential and varietal constituents. Hypersthene occurs in place of chlorite or more abundantly in scattered masses enclosed within the chlorite facies. It does not characterize the whole mass.

Marshall granite is a migmatitic-looking gray rock composed of fine- to medium-grained bands of chloritized biotite gneiss and leucocratic granite. The granite bands are generally only a few millimeters wide, but frequently occur in lenses several feet wide. Quartz veins are numerous.

Lovingston gneiss consists of a medium-grained, dark-gray, porphyroblastic gneiss and granite. It contains potash feldspar, plagioclase, blue and smoky quartz, and biotite. In the gneiss, feldspar with more or less included quartz forms augen-like and irregular masses up to an inch or more in diameter. Biotite in the Lovingston granite occurs in clusters about equal in size and quantity to the felsic portion of the rock. Small lenses and oval masses of leucocratic granite like that in the Marshall occur all through the Lovingston.

A study of the petrology of the granitized complex now in progress has led to the conclusion that the Lovingston, Marshall, and hypersthene granodiorite are intergradational and represent stages of granitization. The parent rock is a meta-sedimentary biotite gneiss and schist. This rock is "early" pre-Cambrian in age.

Numerous pebbles and some cobbles of rock from the granitized complex form conglomerates at the base of the Lynchburg as well as in the Swift Run (Oronoco), Catoctin, and Unicoi formations.

RELATIVE AGES IN THE GRANITIZED COMPLEX

The age of metamorphic rocks customarily depends upon the age of the unmetamorphosed equivalents and not upon the

age of the metamorphism. The age of magmatic rocks depends upon the age of emplacement or crystallization. Rocks formed by replacement are metamorphic and the age should depend upon the age of the unmetamorphosed parent rock. Some geologists now believe that all granitic rocks are formed by a process that is metamorphic in character (Perrin and Roubault, 1949). If granitic rocks are found to be formed by replacement, age relations established on the basis of a magmatic origin in the complexes that contain them need revision. In general, the age-relations problem is simplified. The Lovings-ton, Marshall, and hypersthene granodiorite are, for example, facies of equivalent age formed from a pre-Cambrian sedimentary complex. The sedimentary rocks were metamorphosed to gneiss and schist. Granitization may have developed during a second stage of metamorphism or it may be an end-product of more or less continuous metamorphism. If the schist and gneiss, on the one hand, and the granitized rocks, on the other, are the results of the same interval of metamorphism, they represent different grades or facies with the original sediment at one extreme and granite at the other.

Skialiths (inclusions) of the metasediment occur in bands from a few feet to almost a mile long and from a few inches to more than 100 feet wide in the granitized complex. These enclaves all have foliation parallel to the foliation of the host rock. Some of them are very similar in appearance to the Lynchburg gneiss, but almost all of them are to some extent granitized.

LYNCHBURG GNEISS

The Lynchburg gneiss was named by Jonas (1927, pp. 844-845) from exposures at Lynchburg in central Virginia. It is exposed in a belt (Geologic Map of Virginia, 1928) that extends from northern Virginia into North Carolina along the northwestern margin of the Piedmont province. Southwest of Lynchburg, where the granitized complex disappears, the Lynchburg formation has an outcrop width of almost 20 miles.

Plate I

Figure 1. Rockfish conglomerate at the base of the Lynchburg formation near Rockfish, Virginia.

Figure 2. Cross-bedding in the Lynchburg formation near Rockfish, Virginia.

Figure 3. Phyllite in the Lynchburg formation.

PLATE I

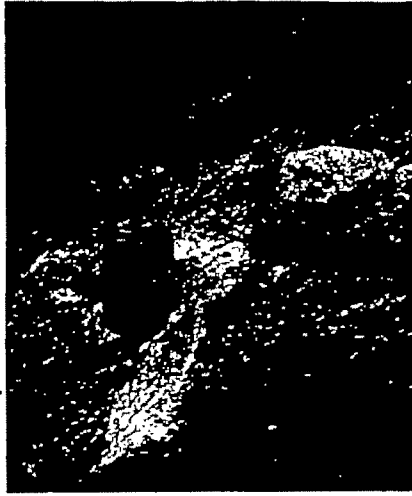


FIGURE 1



FIGURE 2



FIGURE 3

PLATE 2

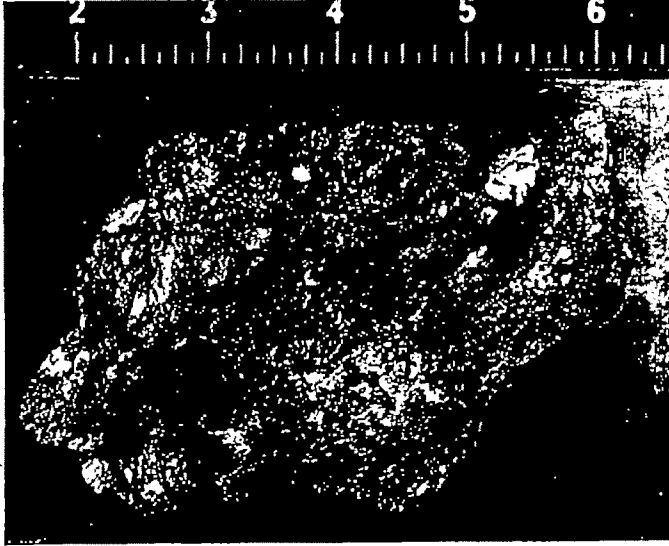


FIGURE 1



FIGURE 2

Northeast of Lynchburg the outcrop belt is only about 5 miles or less wide.

From Rockfish River northeastward, the Lynchburg is bordered on the southeast by the Catoctin and on the northwest by the Lovingsston gneiss of the granitized complex. In its northeastern extension, the Lynchburg is shown on the Geologic Map of Virginia interfingering with the Loudoun formation.

Lithology.—The Lynchburg in central Virginia consists of well-sorted, stratified, and interbedded conglomerates, sandstones, and siltstones that have undergone varying degrees of metamorphism (plate 1, fig. 1). In the vicinity of Rockfish, on Rockfish River, the base of the formation is characterized by a boulder conglomerate. This conglomerate, named Rockfish conglomerate by Nelson (1932), consists of about 1000 feet of boulders, cobbles, and large pebbles contained in a matrix of metamorphosed coarse-grained, arkosic sandstone (plate 1, fig. 2). This conglomerate grades upwards into the main mass of the Lynchburg with a gradual decrease in the size of the phenoclasts. Downward, the conglomerate grades into the granitized complex through from 10 to 100 or more feet of ancient regolith. This former regolith can be distinguished with difficulty from the underlying granitic rock by the appearance of some vestige of stratification, rounded phenoclasts, a change in the lithologic structure, or a change in mineral proportions. Phenoclasts gradually increase in number and size and stratification becomes more pronounced upwards through the ancient regolith into the conglomerate. The lithic and mineral phenoclasts were derived from the underlying granitized complex. The lithic phenoclasts have precisely the same petrography as certain facies in the granitized complex. They are granitic in character. None of the gneissose or schistose facies of the granitized complex occur for certain in the conglomerate. These facies are decomposed by weathering and are not represented by fragments in the present weathered mantle over the granitized complex. The granitic facies, on the other hand, is abundantly represented in the float. In fact, the

Plate 2

Figure 1. Graywacke conglomerate in a sedimentary member in the Catoctin formation in central Virginia.

Figure 2. Sedimentary member in the Catoctin formation at Rockfish Gap in central Virginia.

profusion of granitoid float is misleading. It might easily give an entirely erroneous impression of the character of the bedrock which is predominantly gneissic beneath a mantle of predominantly granite boulders in a clay matrix. The gneissose rock weathers to clay with more or less sand depending upon the quartz content of the bedrock.

Northeast and southwest of Rockfish River, along the strike, the basal boulder conglomerate disappears at the end of a mile or two except for lenticular bodies seen from place to place. Where the Rockfish conglomerate is well represented in the section, there is, in the adjacent granitized complex, the most extensive development of granitic rock. Such a relationship is due to the resistance of the granitic facies to weathering compared to the micaceous facies.

The Rockfish in the type locality resembles a fanglomerate. The relief, however, was not great at the place and time of deposition. Otherwise the comparatively thick residual regolith at the base of the conglomerate could not have accumulated. The phenoclasts, furthermore, probably owe most of their sphericity to spheroidal weathering and not to corrasion.

Above the Rockfish conglomerate, the Lynchburg consists of thick-bedded, arkosic, pebble conglomerate and gravelly sandstone interbedded with thin-bedded, fine-grained, arkosic sandstone and siltstone. The conglomeratic beds range from less than a foot to as much as 25 feet thick. They are more numerous and thicker toward the bottom of the formation than toward the top. Pebbles are very well-rounded quartz of nearly uniform size in a given bed, but somewhat variable from bed to bed. They range from about 1 mm. to 15 mm. in size. The matrix of the conglomerate, before metamorphism, was a sandy to silty aggregate of quartz, clay, sericite, potash feldspar, and plagioclase.

The thin-bedded, fine-grained sandstone and siltstone layers, intercalated with the pebble beds, range from a few inches to a hundred or more feet thick (plate 1, fig. 3). The finer-grained facies consisted of quartz and sericite with only minor amounts of feldspar before metamorphism. Microscopic grains of biotite are concentrated in streaks and bands. Some of the black banded metasiltstone contains graphite (Stose and Stose, 1949, p. 310).

The Lynchburg is predominantly in the biotite stage of

metamorphism. In the Rockfish conglomerate, especially, but also somewhat higher in the formation, granoblasts of potash feldspar and quartz are conspicuous. These granoblasts are formed from detrital minerals and not from introduced solutions. They are believed to be a product of the regional or dynamothermal metamorphism.

The Rockfish conglomerate is a quartz, potash-feldspar, oligoclase gneiss. The folia inclose large phenoclasts which have been only slightly deformed by metamorphism. Potash feldspar porphyroblasts are abundant. Some are ovoid in shape with the long axis parallel to the foliation. Many porphyroblasts are very irregular in shape and have boundaries that cut across the folia.

Above the conglomeratic gneiss at the base, the Lynchburg consists of interbedded biotite and sericite phyllite, fine-grained schists, and medium-grained biotite gneiss.

In places, there are beds in the Lynchburg that are only inconspicuously metamorphosed. These beds are sandstones composed of more or less well-rounded quartz grains.

No limestone or dolomite or their metamorphic equivalents have been found in the Lynchburg in central Virginia.

Thickness.—The bedding and foliation throughout the Lynchburg are approximately parallel. A persistent southeast dip ranges between about 70° and 90° . The formation is some 4.5 miles wide across the outcrop in the Rockfish River section and appears to be about 20,000 to 22,000 feet thick. No conspicuous isoclinal folding is recognized. The massive pebbly and gravelly beds are not flexed so that they can be traced around the troughs or crests of isoclines or other folds. However, the intervening phyllites have folia parallel to the contact with the massive beds, but very much contorted bedding. The massive beds are not continuous, but terminate abruptly or by gradual thinning and gradation into the phyllites. Where the massive beds are abruptly terminated they may have been broken by flexure, but the tapered and sometimes bifurcated terminations were formed by facies gradation. The massive beds, consequently, are contained as lenses or large tabular masses in the siltstone and argillaceous sandstone now represented by phyllite and schist. When the Lynchburg was folded, the fine-grained rock probably "flowed" around the lenses of massive rock which rotated until they

were oriented normal to the regional stress. Where a massive lens lay across the axial plane of a developing fold, it broke to form huge boudinage-like masses that eventually occupied the limbs of the finished fold. The fine-grained, relatively incompetent rock was thinned by flowage between the massive lenses and thickened in the crest and trough zones.

Through some such process the Lynchburg might be actually isoclinally folded without the structure being readily apparent. Its thickness may then be very much less than 20,000 feet.

Stratigraphic relations.—The Lynchburg formation northeast of Lynchburg, Virginia, unconformably overlies the granitized complex and concordantly underlies the Catoctin greenstone. The lava from which the greenstone was formed was evidently extruded upon the nearly horizontal surface of the Lynchburg sediments before they were subjected to orogenic deformation and metamorphism. East of Lynchburg, Virginia, the Catoctin disappears and the Lynchburg is in contact with the Wissahickon formation. On the Geologic Map of Virginia (Virginia Geol. Survey, 1928), this contact is delineated as a fault. Northeast of Lynchburg, this fault is drawn between the Catoctin and Wissahickon. Jonas (1929, pp. 507-509) believes that the fault is indicated by a belt of diaphthorite. In central Virginia, the rocks designated as diaphthorite appear to be phyllites that have not undergone retrogressive metamorphism (diaphthoresis). A well-exposed section crossed by Rockfish River has been studied and found to contain beds of sandstone only about 5 mm. thick in the phyllites. Had these rocks been mylonitized and retrogressively metamorphosed, such delicate features as these layers of sandstone could not have survived.

There may be faults from place to place near or along the southeastern contact of the Lynchburg, but they are probably of comparatively limited extent. In fact, in the foliated rocks of the Piedmont, the identification of faults, in general, is very difficult because of the similarity of the rocks and the sparsity of reference beds or formations.

Perhaps thrust faults do not form in broad expanses of foliated rocks orogenically deformed only once. The displacement concentrated along a thrust fault in comparatively massive, competent rocks might be dissipated over a wide zone in foliated rocks by comparatively infinitesimal movements along a succession of folia. The foliated rocks, in other words, might be

the root zone of thrust faults. Such a relationship is indicated along some thrust faults in the Blue Ridge. Here well-defined faults can be traced into zones of mylonitization which in turn grade into regionally foliated rocks where the fault is lost.

Until more convincing evidence of a fault contact between the Lynchburg or Catoctin and the Wissahickon is found, the Lynchburg or Catoctin may be presumed to underlie the Wissahickon concordantly. An unconformity may be indicated by the disappearance of the Catoctin near Lynchburg. On the other hand, inasmuch as the Catoctin is an effusive, the flows may have, in places, interrupted sedimentation which was elsewhere uninterrupted. This seems to account for the disappearance of the Catoctin more satisfactorily than erosion because there is no evidence of conglomerates composed of greenstone fragments in the critical zone.

The relationship of the Lynchburg, as shown on the Geologic Map of Virginia (Virginia Geol. Survey, 1928), indicates two separate and distinct formations. In the vicinity of Rockfish River, the Lynchburg formation obviously unconformably overlies the granitized complex. West of Lynchburg, Virginia, and in the vicinity of Bedford, Virginia, the Lynchburg formation, as shown on the Geologic Map of Virginia, grades into the Lovingson facies of the granitized complex. This gradation is expressed by a gradual increase in the size and number of feldspar and quartz porphyroblasts toward the Lovingson. Throughout the Lovingson, enclaves of the meta-sediment are numerous. These relations indicate granitization (feldspathization).

The same formation could not unconformably overlie a granite complex in one place and grade into it in another. The Lynchburg in the type locality and northeast of Lynchburg, Virginia, is younger than the "Lynchburg" west of Lynchburg. The two formations resemble each other, but the older formation locally appears migmatitic. In this paper, the name Lynchburg refers to the younger formation. No attempt will be made to describe or propose a name for the older formation. Its relationship to the Lynchburg and other formations and its petrography need to be studied more thoroughly.

Northeast of Lynchburg, the Lynchburg formation is shown more or less intercalated with the Loudoun formation on the Geologic Map of Virginia (Virginia Geol. Survey, 1928). This

map was made when it was thought that the Lynchburg is one of the oldest rocks in Virginia and the Loudoun is Lower Cambrian in age (Jonas, 1927, pp. 844-845). It has been found that the Lynchburg and the associated so-called Loudoun intercalations are undifferentiable. Presumably, some of the only slightly metamorphosed zones in the Lynchburg were identified as a definitely distinct and younger formation. All of the rocks between the Catoctin belt on the southeast and the granitized complex on the northwest are Lynchburg. They have been studied in some detail from northeast of Charlottesville to Lynchburg and reconnoitered into northern Virginia. The stratigraphy in Loudoun County, in northern Virginia, appears to be somewhat confused. Keith (1894) mapped and named the formations in the Blue Ridge and Piedmont in Loudoun County. Evidently he chose an exposure near Aldie as the unspecified type section of the Loudoun in preference to some locality along the northwest side of the Blue Ridge. The formation in the "type" locality, however, seems to underlie the Catoctin and is thus equivalent to the Lynchburg, whereas the "Loudoun" along the northwest side of the Blue Ridge overlies the Catoctin. This presents something of a dilemma because the "Loudoun" along the northwest flanks of the Blue Ridge is younger than the "Loudoun" in the "type" locality. The formation at the base of the Chilhowee group in northern Virginia, has long been established in the literature as the Loudoun. On the other hand, it appears that the Lynchburg and Loudoun in the respective type sections are approximately equivalent. According to rule, the name Lynchburg should be abandoned and replaced by the older name Loudoun. Another name would then have to be given to the basal formation in the Chilhowee group in northern Virginia. If the Weverton is a well-defined unit, the name Unicoi could not be properly extended to include the problematical formation. However, if the Weverton is a facies of indefinite position, as in central Virginia, perhaps the name Unicoi would be appropriate. Although contrary to rule, the simplest solution might be to retain the name Loudoun as it is now used in northern Virginia, and apply the name Lynchburg to the formation beneath the Catoctin.

Nowhere does the Lynchburg cover all of the granitized complex and form a continuous section into the Blue Ridge. It is exposed in the southeast limb of the Catoctin-Blue Ridge

anticlinorium (fig. 4). In the northwestern limb of this fold, in the Blue Ridge, the Catoctin is, in places, separated from the granitized complex by a sedimentary formation from 0 to several hundred feet thick. This formation was named Oronoco by Bloomer (1947, p. 95) and Swift Run by Stose and Stose (1946, pp. 18-19).

In the granitized complex between the Oronoco-Swift Run belt on the northwest and the Lynchburg formation on the southeast, there are, in central Virginia, no known major faults that interrupt the continuity of the section. It is thus reasonably certain that the Oronoco-Swift Run formation is the thinned western edge of the Lynchburg. This relationship is also indicated by the occurrence of Catoctin greenstone above the Lynchburg on the southwest and above the Oronoco-Swift

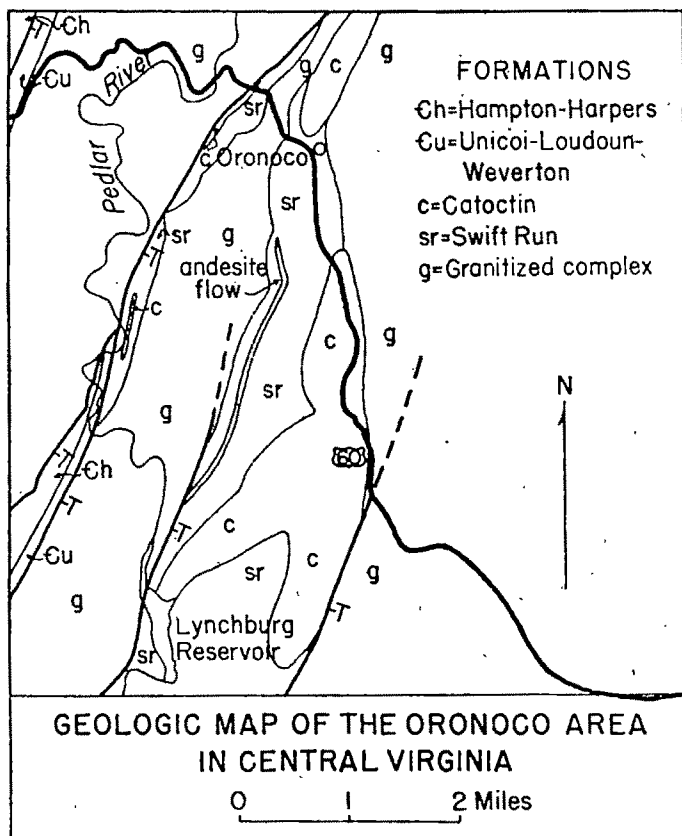


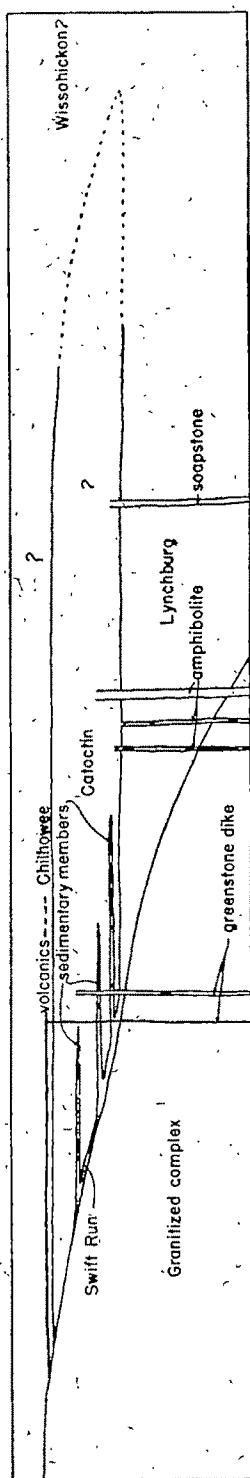
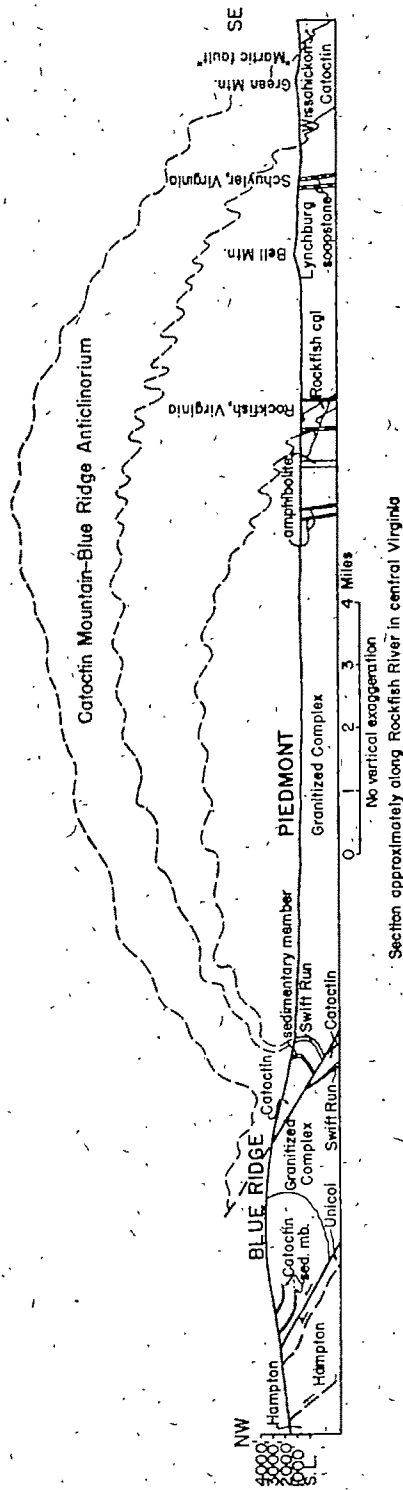
FIGURE 3

Run on the northwest. The Catoctin is presumed to be a once unbroken tabular body of lava flows now exposed in two belts in the opposite limbs of a large anticlinal fold.

The Lynchburg, thus, overlaps the granitized complex from east to west and attains its full thickness in a vast basin of deposition east of the Blue Ridge. The basal conglomerate of the Lynchburg and sediments in the Oronoco-Swift Run and Catoctin formations derived from the granitized complex and the overlap relations clearly indicate the transportation of sediment from west to east.

SWIFT RUN (ORONOCO) FORMATION

Stose and Stose (1946, pp. 18-19) identified about 50 feet of arkosic sandstone, conglomerate, and tuff between the Catoctin and the granitized complex (granodiorite). They named this formation Swift Run for exposures near Swift Run Gap in Rockingham County near Elkton, Virginia. Bloomer and Bloomer (1947, p. 95) subsequently used the name Oronoco for a similar formation between the Catoctin and the granitized complex, in Amherst County near Oronoco Post Office. Stose and Stose (1949, p. 311), in a later paper, claim that the Oronoco is the same as the Swift Run. They state that the formation can be traced from Swift Run Gap to Oronoco Post Office. It is probable that the name Oronoco is not valid and that it should be replaced by the name Swift Run or Lynchburg. However, about a mile northeast of Oronoco Post Office, the Oronoco disappears by overlap from beneath the Catoctin. This particular mass of Catoctin and the underlying Oronoco-Swift Run are isolated by thrust faults (fig. 3). No Catoctin or Oronoco-Swift Run is known southwest of James River, a few miles southwest of Oronoco Post Office. Northeast of Oronoco, the Catoctin is not exposed in the section for about 15 miles. The southwestern end of a belt of Catoctin that extends along the Blue Ridge into Maryland is located near Tye River Gap. In places, the Catoctin in this belt is underlain by a sedimentary formation and in places it rests directly upon the granitized complex. Also the base of the Catoctin is overthrust, from place to place, by the granitized complex. Some of these fault contacts are several miles long. One is easily accessible on the Chesapeake and Ohio Railway at Afton, Virginia. Faults and overlap, consequently, prevent tracing the



Oronoco into the type section of the Swift Run, about 70 miles to the northeast. There are, furthermore, in the Catoctin a number of sedimentary members from a few to nearly 1,000 feet thick. Most of these sedimentary members are composed of rocks very similar to those in the Oronoco or Swift Run. Because the Catoctin evidently overlaps the granitized complex from east to west, any one of a succession of sedimentary members might from place to place underlie the greenstone.

Furcron (1939, pp. 37-41) identified an undisclosed thickness of metasedimentary rocks beneath the Catoctin in Fauquier County in northern Virginia which he named the Fauquier formation. He believes the Fauquier may be equivalent to the Lynchburg.

In the Rockfish River section of the Blue Ridge, the sedimentary formation between the Catoctin and granitized complex is probably the thin margin of the Lynchburg overlap. The Oronoco and Swift Run are, consequently, equivalent to some part of the Lynchburg or Catoctin depending upon the gradient of the pre-Lynchburg erosion surface and the distance up this slope (fig. 5). The Lynchburg was named before any of the formations in question except the Catoctin. However, because they are only locally and partly equivalent and the lithology is very noticeably different, perhaps the extension of the name Lynchburg to include the rocks now differentiated as Swift Run or Oronoco would be incorrect. Furthermore, the name Oronoco should be abandoned in favor of Swift Run with the understanding that the vertical position thickness and lithology of the formation may vary from place to place. Relative to the granitized complex, the Swift Run occupies about the same position as the Rockfish conglomerate, an earlier-named unit. Some geologists, consequently, may favor the name Rockfish in place of the name Swift Run. The Rockfish is overlain by the Lynchburg of which it is a facies, whereas the Swift Run is overlain by the Catoctin. It thus may be preferable to restrict the Rockfish to the Piedmont and retain the name Swift Run.

Lithology.—The Swift Run in central Virginia consists of from 0 to more than 400 feet of graywacke and arkosic conglomerate and sandstone, tuff, and thin greenstone and andesitic effusives of limited extent. One of the best sections is exposed along U. S. Route 60 east of Oronoco Post Office (fig.

8). About one mile southwest of this section, an andesite of volcanic origin is present near the middle of the Swift Run. Other good but comparatively inaccessible sections are located near the head of Rockfish River in Nelson County.

The lithology of the Swift Run varies from place to place. It grades downward into the underlying granitized complex through 10 to more than 50 feet of ancient regolith. In steep or overturned limbs of folds, the ancient regolith is represented by sericitic phyllite. Where dips are gentle there is little metamorphism.

The ancient regolith grades upwards into a conglomerate composed locally of boulders and cobbles and extensively of pebbles of granite, quartz, and feldspar in a micaceous matrix. This conglomerate grades upwards into a coarse- to medium-grained, greenish-gray graywacke. In a few sections, near the top, the Swift Run contains a 20-foot bed of cross-bedded sandstone composed of clear quartz grains with a matrix of introduced epidote. The quartz grains are uniform in size, well rounded, and frosted.

From east to west, the Swift Run converges until it disappears from beneath the Catoctin greenstone. The regolith extends to the margin of the overlap and beyond, but is not everywhere recognized between the Catoctin and granitized complex. In other words, the Catoctin, in a few places, appears to rest upon comparatively undecomposed and undisintegrated granite.

Localized greenstone flows in the Swift Run, not more than about 20 feet thick, are petrographically indistinguishable from the Catoctin greenstone and greenstone flows in the lower part of the Unicoi. Near Oronoco, the flow in the Swift Run has not been altered to greenstone and its original petrographic character is easily discernible. It is an ophitic andesite composed essentially of andesine and minor amounts of biotite, quartz, and potash feldspar.

CATOCTIN FORMATION

The Catoctin was named by Geiger and Keith (1891, plate IV) from exposures in Catoctin Mountain near the northeastern end of the Blue Ridge province. It is exposed in two parallel belts that extend into central Virginia. One belt caps the main mass of the Blue Ridge and the other belt occurs in an alignment of ridges about 20 miles to the southeast. In cen-

tral Virginia, the northwestern belt of the Catoctin is thrust upon the Chilhowee group, but farther northeast it underlies the Loudoun. In some places, the Catoctin in the northwestern belt overlies the Swift Run or granitized complex. Elsewhere, the granitized complex has been thrust upon the Catoctin and the base is unexposed. The southeastern belt, southeast of the Blue Ridge, is part of the southeastern limb of the Catoctin Mountain-Blue Ridge anticlinorium. Therefore, the Catoctin in central Virginia is exposed in both limbs of a major anticlinal fold. This fold has been truncated by erosion to a depth equivalent, at least, to the combined thickness of the Catoctin and Lynchburg formations. Along the northwestern limb of this fold near the Catoctin belt there are a few outliers of the Catoctin underlain by Swift Run. No other outliers of the Catoctin or underlying metasedimentary rocks are known with the possible exception of slate in a body about one-half mile wide and 6 miles long at Mechum River midway between Rockfish Gap and Charlottesville. This body is located near the axial zone of the Catoctin Mountain-Blue Ridge anticlinorium. Little is known of this slate. It is metasedimentary and may be a down-faulted mass equivalent to some part of the Lynchburg.

Lithology.—The Catoctin formation consists of about 5000 feet of greenstone with widely separated, discontinuous sedimentary members. These sedimentary members range from a few inches to as much as 750 feet thick (plate 2). Owing to secondary alteration, it is difficult to ascertain the original composition of the greenstone. Although no unaltered specimens have been found, some are more altered than others. The primary texture is clearly ophitic and fine-grained with scanty phenocrysts. Amygdules, veins, pods, and small irregular masses of milky quartz; milky quartz and epidote; or milky quartz, epidote, and potash feldspar occur irregularly throughout the formation. In the northwestern belt, the Catoctin is massive except locally along some faults. The Catoctin in the southeastern belt (in the Piedmont), on the other hand, is a green schist or phyllite.

Andesine, as remnants and "ghosts", is the only certainly identified primary mineral. It comprises at least 50 per cent of the primary composition.

The interstices among laths of feldspar are occupied by ag-

gregates of secondary minerals in which tiny remnants of biotite and a pyroxene (augite?) have been noted. These minerals are presumably relics of the primary mafic minerals. In only a few, among many specimens studied, small grains of quartz and potash feldspar have been identified. Some of these grains may be primary.

Secondary minerals obscure or obliterate the primary minerals and primary texture of the greenstone. These secondary minerals include an abundance of epidote and chlorite and variable amounts of sericite, tremolite, actinolite, clinozoisite, quartz, potash feldspar, hematite, ilmenite, and leucoxene.

The primary composition of the Catoctin is so obscured by secondary minerals that classification is difficult. Keith (1894, pp. 302-309) recognized altered basalts, andesites, and rhyolites in northern Virginia. More recent writers generally refer to the greenstone as a metabasalt. In central Virginia, indirect evidence seems to indicate andesite (Bloomer and Bloomer, 1947, pp. 99-100).

No rhyolite has been found in central Virginia. Layers of red slate in the greenstone and in sedimentary members of the greenstone resemble rhyolite, but are probably metamorphosed tuffs.

The altered Catoctin is widely known as greenstone. The writer (Bloomer and Bloomer, 1947, p. 100) is responsible for classifying these effusives as propylite. He thought the term greenstone too generalized. However, there is probably no important objection to the term "greenstone".

In some ways, the Catoctin resembles spilite. No pillow structure, common in spilite, has been identified nor is it known for certain whether or not the Catoctin was extruded subaqueously. However, it does seem to be part of a geosyncline and its composition approximates spilite.

In the Love area (fig. 2) of the Blue Ridge, several sedimentary members have been mapped in the Catoctin. These members consist of from 0 to as much as 750 feet of graywacke pebble conglomerates and sandstones, epidotized quartz sandstones, and thin beds of red tuff. The pebbles are predominantly quartz, but some are granite and feldspar. No greenstone or Lynchburg gneiss pebbles have been found.

Locally the conglomerate consists of angular pebbles of feldspar and quartz in a micaceous matrix and resembles

granite. A careful search or traverse along the strike reveals well-rounded and frosted pebbles, stratification, and facies gradation.

Stratigraphic relations.—The Catoctin overlaps the Lynchburg, Swift Run, and granitized complex from east to west (figs. 2, 3, 4, 5). In northern Virginia, the Catoctin is overlain by the Chilhowee group. In central Virginia, it is thrust-faulted upon the Chilhowee group so that the stratigraphic relationship is unexposed and must be extrapolated. Near Tye River Gap, the Chilhowee group rests unconformably upon the granitized complex. Consequently, the Catoctin must disappear from beneath the Chilhowee. Although the disappearance may be attributed to erosion, the major cause is probably due to overlap or convergence. This conclusion is supported by several indirect lines of evidence as follows:

1. Conglomerates at the base of the Chilhowee group contain no pebbles of greenstone, but an abundance of granitic detritus. How could the sediments in the base of the Chilhowee have been transported from east to west more than 20 miles across an eroded surface of Catoctin and be devoid of greenstone (figs. 4, 5)? Furthermore, where did the granite come from? These sediments must have moved from west to east and the Chilhowee must be part of a succession of overlapping formations beginning at least with the Lynchburg.

2. The Swift Run overlaps the granitized complex from east to west. The Catoctin is concordant with this formation and must similarly overlap it and somewhere disappear beneath the Chilhowee.

3. At Love (fig. 3) about 6 miles northeast of Tye River Gap, the Catoctin is separated from the granitized complex by the Swift Run. This locality is probably near the *northwestern* margin of the Catoctin. About a mile northeast of this exposure there is a succession of several sedimentary members in the Catoctin. Unfortunately, in this locality the Catoctin lies between thrust faults. However, the proximity of the Swift Run and the sedimentary members may indicate the proximity of the northwestern margin of the Catoctin overlap. The sedimentary members contain no greenstone detritus. Furthermore, their greater thickness and frequency here, compared to the middle and southeastern margin of the Catoctin belt, suggests they are broad fans that spread and

finally disappear from west to east over greenstone (figs. 4, 5). Also, along the western margin of the greenstone, some or all of the sedimentary members may merge into the overlapping Swift Run formation. These relations indicate overlap.

4. At or within a few feet of the base of the Chilhowee, there are volcanic flows and tuffs (Furcron and Woodward, 1936). These volcanic rocks are not more than 25 feet thick and the flows are absent in many sections. The flows are, in some places, only slightly altered, but in some places they are greenstones. The tuffs are represented by red slates. These greenstones and slates are petrographically similar to the greenstones and tuffaceous slates in the older Catoctin formation (plate 3).

If the Catoctin overlaps the granitized complex from east to west, the volcanic rocks at the base of the Chilhowee may represent the thin, western margin of the overlap. In other words, the Chilhowee volcanics represent the last of a series of eruptions now largely represented by the Catoctin.

CHILHOWEE GROUP

Little need be said here about the Chilhowee group aside from a statement to remind the reader of certain relations. Although Resser (1933, pp. 743-746) proposed that the Chilhowee formations (Hampton and Unicoi) beneath the Erwin be considered pre-Cambrian (Beltian), but Paleozoic in age, most geologists agree that the whole group is Lower Cambrian in age.

In northern Virginia, the Chilhowee rests upon Catoctin greenstone, but in central and southwestern Virginia, it rests upon the granitized complex. There can be no doubt of an unconformity at the base of the Chilhowee. There is, however, a question regarding the magnitude, significance, and nature of this unconformity. Before this question can be satisfactorily answered, the attitude and relations of the Catoctin must be established. In the preceding pages, an attempt has been made to do this. The Catoctin seems to overlap successively the Lynchburg, Swift Run, and granitized complex from east to west.

There is no conspicuous evidence of an angular unconformity between the Catoctin and the Chilhowee. Along the margin of

the overlap such an unconformity might seem to appear, but the angularity in such a case would be horizontal and not vertical. In other words, it would not indicate the orogenic deformation of the Catoctin prior to the deposition of the Chilhowee. Where the Chilhowee overlies the Catoctin it is difficult to prove or disprove an angular unconformity because of the absence of well-defined flow-boundaries in the greenstone. Sedimentary members in central Virginia clearly reflect the structural attitude of the greenstone. If such members occur in the Catoctin where it is overlain by the Chilhowee, the structural relations can be ascertained. Unfortunately, in central Virginia where there are numerous sedimentary members, the Catoctin is thrust faulted upon the Chilhowee. On the other hand, in northern Virginia, where the Chilhowee overlies the Catoctin, sedimentary members seem to be scarce or absent or mistaken for other formations.

The conglomerate rocks in the basal portion of the Chilhowee contain pebbles of quartz and granite, but appear to be devoid of greenstone or tuff pebbles. Rare fragments have been found that resemble these rocks, but microscopic examination reveals them to be fine-grained graywackes colored by chlorite, sericite and siltstones with a dense matrix of hematite. Not a single specimen of indisputable greenstone or tuff has been found in the conglomerates.

If the Catoctin occurs extensively beneath the Chilhowee and the Chilhowee conglomerates were transported from east to west across several miles of Catoctin (figs. 4-5), why are the Chilhowee basal conglomerates almost, if not completely, devoid of greenstone fragments? Obviously the sediment must have come from the west and at least the basal portion of the Chilhowee must overlap the granitized complex from east to west.

Such a relationship between the Catoctin and the basal Chilhowee suggests that these formations may not be separated by an unconformity that indicates a major difference in their ages.

Another feature that seems to provide a basis for the correlation of these formations is the volcanic rocks in the base of the Chilhowee. Bloomer and Bloomer (1947, pp. 103-106) conclude that these volcanics and those in the Catoctin are petrographically similar. Stose and Stose (1949, pp. 314-315)

somehow concluded that Bloomer and Bloomer mistook the Chilhowee volcanic rocks for Catoctin and the underlying Chilhowee sedimentary rocks for Swift Run. Bloomer and Bloomer not only recognize the volcanics in question as Chilhowee, but see in them a key to the relationship of the Catoctin and the Chilhowee. Stose and Stose (1949, p. 315) also state that the volcanics in the Chilhowee do not resemble those in the Catoctin and Swift Run. It is true that in places the effusive in the Chilhowee is a black, basaltic rock unlike any rock yet found in the Catoctin. This black, basaltic rock is petrographically very similar to the effusive near the middle of the Swift Run near Aronoco (fig. 3) in Amherst County. Furthermore, the Chilhowee effusive is a greenstone in places. This greenstone may be seen on the Blue Ridge Parkway at White Rock (fig. 2) overlook about 7 miles northeast of Tye River Gap; on the north side of James River about one-half mile downstream from the Snowden bridge where U. S. Route 501 crosses James River; on Virginia Route 56 just west of Tye River Gap; and at other places. In hand specimens and thin sections, this Chilhowee greenstone is indistinguishable from Catoctin greenstone. Also, spectrochemical analyses (table 2) of these greenstones reveal the same elements. The trace elements are presumably fortuitous and would hardly be duplicated in rocks of widely different ages from different sources.

Above the basal conglomerate, the Chilhowee grades into marine deposits. In the middle and top of the group, there is

TABLE 2

Spectroanalyses of Greenstone and Basalt						
1	2	3	4	5	6	7
Al	Al	Al	Al	Al	Al	Al
Ba	Ba	Ba	Ba	Ba	Ba	Ba
Ca	Ca	Ca	Ca	Ca	Ca	Ca
Cu	Cu	Cu	Cu	Cu	Cu	Cu
Fe	Fe	Fe	Fe	Fe	Fe	Fe
K	K	K	K	K	K	K
Mg	Mg	Mg	Mg	Mg	Mg	Mg
Mn	Mn	Mn	Mn	Mn	Mn	Mn
Na	Na	Na	Na	Na	Na	Na
Si	Si	Si	Si	Si	Si	Si
Sr	Sr	Sr	Sr	Sr	Sr	Sr
Ti	Ti	Ti	Ti	Ti	Ti	Ti

1. Unicol greenstone in the James River section.
2. Unicol greenstone at White Rock overlook on the Blue Ridgeway.
3. Catoctin greenstone northeast of Love, Virginia.
4. Catoctin greenstone in Green Mountain.
5. Amphibolite near Rockfish, Virginia.
6. Basalt in the Triassic of New Jersey.
7. Metabasalt in the pre-Cambrian of Michigan.

an abundance of siliceous sandstone (orthoquartzite) formed from pure quartz sand. The uppermost sandstone grades into Shady dolomite. These rocks are unquestionably parts of the Appalachian geosyncline in which the sediment came, at least in part, from the east. A reversal of the direction of the movement of sediment must have occurred sometime during the deposition of the Chilhowee. This raises problems that cannot be answered until more work is done. Presumably the landmass west of the Blue Ridge was peneplaned and flooded by the sea. The sediments deposited in this sea may have come from the basal Chilhowee, Catoctin, Swift Run, and Lynchburg formations that were to some degree elevated to the east. This presupposes that deposition to the east terminated, which is by no means certain. In fact, while the validity of the Martic overthrust is in doubt, there is the possibility that the Wissahickon is a metasedimentary formation deposited upon the Catoctin and Lynchburg. Such a possibility not only indicates a continuation of sedimentation to the east, but requires that the Chilhowee group and possibly younger formations are in some part equivalent to the Wissahickon. Where then were the lands that drained to the sea in which these sediments were deposited? The Wissahickon presumably formed for the most part from impure clastic sediments with only minor amounts of interbedded limestones. Above the Chilhowee the formations contain much limestone and dolomite. This suggests the facies became more clastic and probably more heterogeneous from west to east. Does this mean that somewhere far to the east there was a landmass and that the surface which the Lynchburg, Swift Run, Catoctin, and lowermost Chilhowee overlap was the low-lying western margin of a basin which spread westward? The Appalachian geosyncline from the Blue Ridge westward would then be the foreland marginal portion of a large geosyncline to the east. This large geosyncline occupies part of the region presumed to have been occupied by the old land of Appalachia. The extension of the Appalachian geosyncline to the east somewhat restricts the western extent of Appalachia. Perhaps this old land retreated eastward as the geosyncline spread eastward and westward.

ALTERED BASIC DIKES

There are many amphibolite, soapstone, and greenstone dikes in the region between the Catoctin formation in the Blue

Ridge and the Catoctin formation in the Piedmont. These dikes are from a few inches to several hundred feet wide and up to several miles long. There is a swarm of them along the boundary between the Lynchburg and the granitized complex (fig. 4). Here, the dikes are not only more numerous, but larger. Although there are exceptions, the greenstone dikes are found in the granitized complex, amphibolite dikes in both the Lynchburg and granitized complex near the contact, and soapstone dikes in the Lynchburg east of the amphibolite dikes. These dikes probably are all genetically related. In some of them, amphibolite grades into soapstone or greenstone. Rarely, greenstone forms a thin zone along the walls of the amphibolite dikes.

All the rock types in the dikes weather comparatively rapidly. They are often represented by a yellowish-brown, plastic clay. Fresh exposures are scarce.

All the dikes parallel or are nearly parallel the strike of the foliation and stratification of the intruded rocks.

The amphibolites, soapstones, and greenstones contain such an abundance of secondary minerals that both the primary minerals and textures have been largely obliterated (plate 4). In some of the greenstones, remnants of feldspars (andesine, Ab_7An_3) and an ophitic texture are apparent. Presumably, the amphibolite and soapstone were formed from a gabbroic rock or the coarse-grained equivalent of the greenstone. This is little more than a guess based upon uncertain relics of minerals and texture and the assemblage of secondary minerals which probably came from a mafelsic rock. These secondary minerals are similar to those in the greenstone and include hornblende, quartz, chlorite, epidote, clinozoisite, sericite, serpentine, calcite, talc, hematite, ilmenite, leucoxene, and probably others. The order of abundance varies. In the amphibolites, hornblende is generally most abundant; in the greenstone, epidote and chlorite; and in the soapstone, talc. There are gradational facies between amphibolite and soapstone in which talc and hornblende (actinolite) are nearly equally abundant.

Spectroanalyses of these dike rocks yield an assemblage of trace elements very similar to those in the Catoctin (table 2). This, the petrographic similarity of the greenstone in dikes to that in the Catoctin, and the location of the dikes suggests that the dikes are the hypabyssal phase of Catoctin volcanism (Furcron, 1939, pp. 26-28).

A comparatively large number and persistence of dikes along the contact zone between the Lynchburg and granitized complex encourage postulation. This zone is located about midway between the northwestern and southeastern Catoctin belts (fig. 4). If the Swift Run is the thin margin of the Lynchburg overlap, the Lynchburg thickens very rapidly. The formation has an apparent thickness of more than 20,000 feet. A true thickness of this magnitude would require an increase of thickness of about 1000 feet per mile from west to east. It is probable, however, that the true thickness of the Lynchburg is something less than 20,000 feet and that the apparent thickness is due at least in part to isoclinal folding and large-scale boudinage structure. In any case, the Lynchburg must be a comparatively thick formation of shallow water sediments. These sediments probably accumulated with synchronous subsidence. Northwest of the Lynchburg, subsidence must have gradually decreased as shown by the thinning and disappearance of the Swift Run. When the Lynchburg had attained a certain thickness, perhaps a hinge zone in the subsiding region had become sufficiently strained to fracture. Magma may have intruded along these fractures and flowed out upon the surface to form the Catoctin. In central Virginia, no dikes have been recognized in the Catoctin. This apparent absence of dikes suggests the Catoctin masses now represented in the section are portions of flows somewhat distant from the main source of the lava.

AGE RELATIONS

Stose and Stose (1949, p. 815) and King (1949, pp. 536-538) are of the opinion that the Catoctin, Swift Run, and Lynchburg are late pre-Cambrian in age. This opinion seems to depend upon an unconformity at the base of the Lower Cambrian Chilhowee group. The fact that the Lynchburg, Swift Run, and Catoctin are, in general, somewhat more meta-

Plate 3

Photomicrographs

Figure 1. Andesite near the middle of the Swift Run formation near Oronoco, Virginia. The feldspars are andesine. Crossed nicols, 62x.

Figure 2. Greenstone from the Catoctin formation near the head of Rockfish River. The feldspars are andesine. Crossed nicols, 62x.

Figure 3. Greenstone from the base of the Unkol formation southeast of Buena Vista, Virginia. The feldspars are andesine. Crossed nicols, 62x.

PLATE 3



FIGURE 1



FIGURE 2

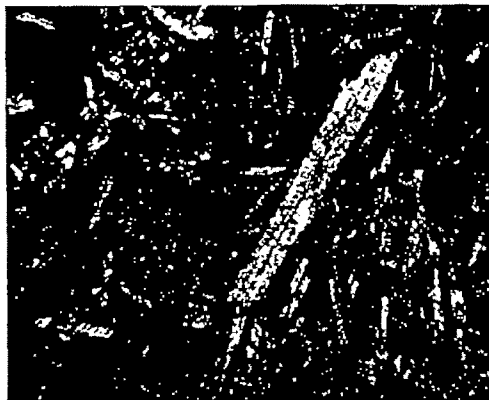


FIGURE 3

PLATE 4

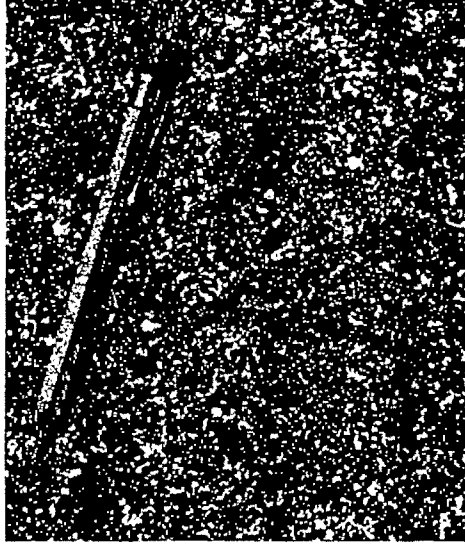


FIGURE 1



FIGURE 2

morphosed and more complexly folded and faulted, probably strengthens the opinion that these formations are pre-Cambrian in age and not closely related to the Chilhowee. Furthermore, it is presumed that the volcanics in the Catoctin are unrelated to those in the Unicoi.

In the Blue Ridge, the structural geology is comparatively complex. Thrust faults fragment folds so that the continuity of exposed cross sections is limited. The Catoctin in central Virginia is thrust upon the Chilhowee so that the stratigraphy is obscured. In northern Virginia, the Catoctin underlies the Chilhowee. Whether or not the boundary is a major unconformity is problematical. If the Lynchburg, Swift Run, Catoctin, and lower portion of the Chilhowee overlap the granitized complex, the unconformity may not be so significant. Furthermore, if the volcanics in the base of the Chilhowee represent the final eruptions of the volcanism that produced the Catoctin, no major lapse of time is represented by the contact. These relations suggest that sedimentation in the region began with the Lynchburg and continued at least into the Chilhowee, interrupted only by volcanism which produced tuffs and effusives in the Swift Run, Catoctin, and lower Chilhowee. During intervals of volcanic quiescence, sedimentation produced members in the Catoctin.

The Lynchburg, Swift Run, Catoctin, and Chilhowee, thus, appear to be in a sequence that is unbroken by an unconformity of more than minor significance. If this is true, the pre-Cambrian-Cambrian boundary must be (1) in the Chilhowee, (2) between the Catoctin and Swift Run or Lynchburg, (3) at the base of the Lynchburg, or (4) between the Chilhowee and Catoctin. The oldest positively Cambrian fossils are found near the top of the Erwin (Antietam) formation. This formation is then incontrovertibly Lower Cambrian in age. It grades downward into the Hampton (Harpers) formation and is part of the Chilhowee group. The pre-Cambrian boundary is below the Erwin. Resser (1933, pp. 743-746) proposed the recognition of the base of the Cambrian at the base of the Erwin. If the boundary is drawn on the basis of fossils, Resser's proposal seems sound. Some geologists might object to including, in the Cambrian, about 600 feet of non-fossiliferous Erwin

Plate 4

Figure 1. Amphibolite in dike near Rockfish, Virginia.

Figure 2. Photomicrograph of amphibolite near Rockfish, Virginia 100 x.

below the fossil-bearing top of the formation. Others, who base their argument upon physical relations, might object to drawing the boundary within what appears to be a more or less unbroken sequence. They prefer to utilize unconformities as time boundaries. In either case, there seems to be reason to doubt the validity of a pre-Cambrian-Cambrian boundary drawn at the base of the Chilhowee. In a given region, an interval of volcanism is presumed to be of comparatively short duration and it does not seem right to correlate such an event so that it is part Cambrian and part pre-Cambrian. There are, however, examples known to all geologists where systemic boundaries are contained within formations. Similarly the pre-Cambrian-Cambrian boundary might be located within a formation or unbroken sequence of formations.

The writer does not know whether the Lynchburg, Swift Run, Catoctin, and lower Chilhowee are Cambrian or late pre-Cambrian. Where appropriate fossils are found the rocks are Cambrian. There is always the chance that such fossils may be found in rocks lower in the section. Until some such acceptable evidence is found, the question of age hardly seems to be a matter for controversy. Most Blue Ridge geologists seem to agree that the formations between the Chilhowee and granitized complex are late pre-Cambrian in age. There is some question as to "how late" these formations are and "how low" the Lower Cambrian. The writer has attempted to prove that the problematical formations are part of a continuous sequence and, therefore, closely related in age.

ACKNOWLEDGMENTS

Since 1941, the Virginia Geological Survey has employed the writer during the summer months to study the geology of the Blue Ridge province. In 1947 and 1948, the National Research Council gave a fellowship which relieved the writer from teaching duties and permitted a session of study at Harvard University as research associate. Any expression of thanks for these opportunities is inadequate.

Y. William Isachsen and Harry J. Werner ably assisted in the field and participated in countless discussions of the problems. The contribution of these men is inestimable. Richard Rezak and John Rodgers critically read and corrected numerous errors in the manuscript. To each of these men, the writer extends sincere thanks.

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INTENSIVE FROST ACTION ALONG LAKE SHORES

STEPHEN TABER

ABSTRACT. The gravel on beaches in the Finger Lake district of New York is mostly limestone, and it is derived from the boulder clay that blankets much of the region. On most beaches the cobbles are angular to subangular, because they are being ruptured by frost action faster than the fragments can be rounded by waves. Water, to feed growing ice crystals which cause rupture, can be drawn into dense-textured, limestone cobbles embedded in wet clay; for water in fine-grained soils and rocks can be undercooled in the immediate vicinity of ice crystals. Coarse-textured rock, such as sandstone, and dense-textured limestones resting on gravel are seldom broken by freezing, and, therefore, become well rounded. Since water occupying the larger voids of sandstone and gravel freezes readily, it cannot be drawn up to ice crystals growing in small voids at slightly lower temperatures.

INTRODUCTION

AT many places along lake shores in the Finger Lake district of New York environmental conditions are extremely favorable for fragmentation of boulders and cobbles by frost action. At other localities along the shores conditions are not so favorable. During a period of many years the writer has made observations at various localities on Seneca, Cayuga, Owasco, Skaneateles and smaller lakes in the district but the most detailed work has been done on the shores of Cayuga Lake.

From the standpoint of frost action, five types of shore line may be distinguished:

1. Beaches with a thin layer of gravel resting on clay or mud probably form the commonest type. The materials on these beaches are derived from the glacial till which blankets most of the region.
2. Beaches having a thick deposit of gravel are found chiefly where small streams flowing in post-glacial gorges reach the lakes.
3. Beaches consisting of thick deposits of sand, silt or mud with no coarse material are found mostly in protected coves and where large deltas have been built at the heads of lakes.
4. Shale beaches, consisting mainly of small fragments of shale, are found where shale crops out along the lake shores.

5. Limestone shores are found where beds of Paleozoic limestones crop out.

The distinction between the different types of beaches is not always sharply defined since there are gradations from one type to another.

BEACHES WITH A THIN LAYER OF GRAVEL ON CLAY OR MUD

Storm waves and windblown ice erode boulder clay along the lake shores with the formation of low scarps at high water level. The coarse material is being concentrated on the beaches and in shallow water, the clay being gradually moved into deeper water. Lake bottoms, except near shore, are covered with soft carbonaceous marl.

The clay is highly plastic when wet but on drying it shrinks with the formation of large cracks and becomes quite hard. The coarse material in the clay is mostly Paleozoic limestone but sandstone, quartzite, gneiss, granite and, more rarely, other rocks are present. Boulders range up to over 7 feet in diameter and most of them are rounded. Many limestone boulders show glacial striae. In contrast, boulders and cobbles on the beaches are smaller in average size and are much more angular than those in the boulder clay. The west-facing beach at Farleys Point on Cayuga Lake is an excellent example of a beach developed on glacial till, and it has been under intermittent observation by the writer for over 40 years.

Farleys Point is a double-headed peninsula jutting into Cayuga Lake from the eastern shore, 1.5 miles southwest of Union Springs. A westward-projecting headland is called Round Point, and one extending northward, Long Point. A profile and section surveyed at right angles to the west-facing beach of Long Point is shown in figure 1. The ground surface is convex upward where it slopes toward the lake and very slightly con-

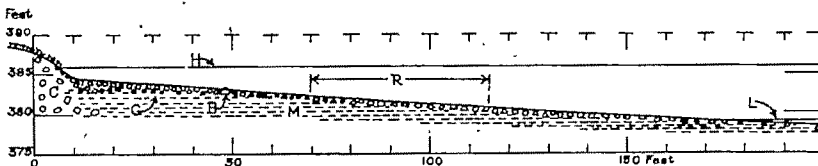


Fig. 1. Profile and section across beach at Farleys Point on Cayuga Lake, New York. H, high water level; L, low water level; B, location of boulder shown in plate 1; C, boulder clay; G, gravel; M, fine mud; R, area where ruptured cobbles shown in figure 2 were obtained.

cave below high water level. The till in which the waves have been cutting is variable in thickness, but, near the line of section and 400 feet from the shore, a well penetrated 30 feet of the boulder clay.

Under natural conditions lake level was usually highest after spring thaws and lowest during the late fall and winter when precipitation is lowest and runoff is retarded by freezing temperatures. However, high water may occur occasionally at any time during the year as a result of abnormally heavy rainfall. In recent years the water level has been regulated by the Department of Public Works of the State of New York which operates the spillway gates and lock of the Barge Canal at the foot of the lake. The water is drawn down in the fall to prevent property damage from ice piled up by onshore winds. During the 6-year period, 1943-1948, the maximum elevation of the lake at the lock, as recorded by the Department of Public Works¹, occurred each year between May 13 and June 19, and varied between 384.8 and 386.4 feet above mean tide. The minimum elevations occurred between February 9 and March 10, and varied between elevation 379 and 380.4 feet. The high-water and low-water lines are, therefore, separated vertically by 7.4 feet, and the horizontal distance between them is 170 feet.

The mean annual temperature at Auburn, near the foot of the lake is 47.3°F., the average minimum temperature is 15.1° and the lowest temperature recorded is -20°. The average date of the earliest killing frost is October 17 and the average date of the latest killing frost is May 2 (Martin, 1984, pp. 26-28).

The west-facing beach at Long Point is protected from south and east winds but is exposed to winds from the north and west. Winds blowing from a little west of north have an 8-mile stretch of water in which to build up waves large enough to cause considerable abrasion, as is proved by the presence of pieces of rounded and frosted glass.

Gravel thrown up by storm waves above high water level rests on till, but a few feet lower it rests on soft mud derived from the till, and this mud grades through calcareous mud into typical fresh water marl a short distance beyond the low-water line. The gravel is from 1 to 2 or more feet thick near the upper

¹ Letter from Mr. Wm. Robinson, District Engineer, dated Sept. 7, 1949.

margin of the beach but, lakeward, gradually becomes thinner, and beyond the low-water line only scattered cobbles are present. A few widely separated stones found in deeper water may have been ice-raftered from the shore.

The two largest boulders on the beach have maximum diameters of 6 and 7 feet. Most of the smaller boulders have been removed in recent years for use in building protective walls in front of cottages facing the lake. Most of the limestone cobbles are about 5 inches in diameter with a tendency toward tabular form. They commonly rest in the mud with a flat side up, the larger ones being more or less surrounded and separated by slightly smaller ones. This imperfect pattern is probably due to wave action.

Most of the cobbles are angular to subangular (plate 1), but many cannot be so simply described, for flat and irregular surfaces with sharp edges occur on the same specimen with well-rounded surfaces. Many water-worn cobbles have been broken so recently that the fragments have not had time to become separated, though wave action and movement of lake ice soon displace such fragments. Seven angular fragments from a brick were found scattered over an area of 20 square yards.

Some typical cobbles, fractured without separation of the fragments, are shown in figure 2. They were all picked up in shallow water within an area of 300 square yards (fig. 1). Similar specimens are common throughout most of the area between the high- and low-water lines. They are most abundant in early summer when, over large areas, they average one or more to 100 square feet, and, locally, may have a density of more than 10 to 100 square feet. Cobbles with vertical or steeply inclined fractures are easier to find but horizontal fractures are perhaps commoner. Most cobbles are broken into two fragments (fig. 2, B, D, E, F) but some are broken into several (fig. 2, A, C). Fragments of a limestone boulder 3 feet in diameter, deeply embedded in mud have remained in place for several years. Some boulders show discontinuous, incipient fractures which, in a year or two, are enlarged and extended with complete separation of fragments. The incipient fractures show up as dark lines on smooth, dry surfaces because of capillary water drawn up from the wet mud in which the boulders are embedded.

Cobbles of sandstone, quartzite, granite and gneiss, in contrast with those of limestone, are mostly well rounded, and only two were found that had been recently broken (fig. 2, F and plate 1). Each of these cobbles has a single smooth, flat surface, apparently a bedding plane, with sharp edge where it cuts the rounded surface. The matching fragments were not found.

No recently fractured boulders or cobbles were observed on the lake floor beyond the low-water shore line, and the few present near the high-water shore line, where the gravel is thickest, may have been brought up by storm waves or ice. The largest boulders and blocks of limestone on the beach seem to be more resistant to rupture than smaller ones for they show no evidence of recent cracks.

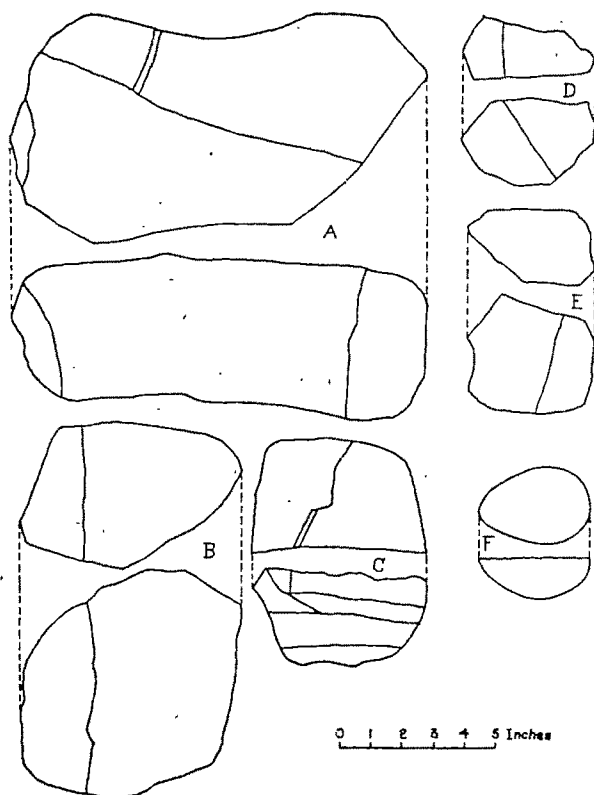


Fig. 2. Profiles of cobbles ruptured by frost action without separation of fragments. A, B, C, D, E, dense-textured limestone; F, coarse sandstone. These cobbles were obtained from the area "R" in figure 1.

A typical view of the mixture of angular, subangular and rounded cobbles present on the beach is shown in the photograph (plate 1) taken in the late summer of 1949 when the lake level stood at 383 feet above mean tide. The cracked boulder in the foreground is well embedded in mud while the smaller cobbles around it rest on other cobbles. The boulder is located about 40 feet from the high-water shore line and at an elevation of 383.2 feet.

BEACHES WITH THICK GRAVEL DEPOSITS

Good examples of beaches with thick gravel deposits are found at the mouth of Big Gully Creek, 2.5 miles southwest of Union Springs, and at Meyers Point, near Ludlowville, where Salmon Creek reaches Cayuga Lake. The gravel, as indicated by the abundance of erratics, has been derived mostly from the till. Boulders, cobbles and pebbles are well rounded, angular fragments being very rare. The high degree of rounding is due to abrasion during stream transportation as well as the later abrasion by wave action, but a more important factor is the absence of recent fracturing which is so noticeable where cobbles rest on clay or mud. The rupturing of cobbles without displacement of fragments is not taking place on beaches with thick gravel deposits.

BEACHES OF SAND, SILT OR MUD

On beaches where only sand, silt and mud are present it is difficult to determine by direct observation the extent to which the coarser particles are being broken up, and the relative importance of the various factors involved.

SHALE BEACHES

The commonest bedrock exposed along the lake shores is shale, which in places, forms high cliffs. It disintegrates readily so that beach material consists chiefly of small fragments of shale. A few erratics from the glacial drift are commonly present and most of these are well rounded. In some places spheroidal concretions are also found.

LIMESTONE SHORES

The limestone beds are too thin to form high cliffs but, in places, as at Round Point and at Frontenac Island, 0.5 mile west of Union Springs, they form low walls and are exposed on the lake bottom. In shallow water limestone blocks and a few erratics rest on the bare limestone, but in deeper water the bed-

rock is completely covered by lake mud. The limestone is broken by jointing into large blocks which show no evidence of recent fracturing.

EXPERIMENTAL EVIDENCE

The extensive rupturing of beach cobbles and boulders cannot be ascribed to impact, wetting and drying, or simple changes in temperature, for these agencies are as active, if not more active, on beaches with thick gravel deposits as on those where the stones rest on clay and mud. Moreover, impact would tend to separate fragments at once, and cobbles that are under water much of the year are subjected to fewer cycles of wetting and drying and to smaller and less frequent temperature changes than those continuously exposed on land. The elimination of these agencies leaves frost action as the explanation of the rupturing, and this process was investigated experimentally in both field and laboratory.

All cobbles and boulders used in the experiments were obtained in digging a well at Farleys Point. Some of these cobbles and boulders were embedded in surface clay 75 feet from the lake shore, some were placed in and on the thick deposit of gravel near the high-water line, and some were embedded in lake mud at points between high and low water. No stones placed on gravel have been broken although exposed for 10 or more years. Most of the boulders embedded in lake mud have been ruptured.

A rounded limestone boulder, 14 inches in diameter, showing glacial striae, was unaffected after 5 years' exposure while resting on well-drained clay, but, when removed to the beach mud, it was broken into 9 angular pieces during a single winter. A subrounded boulder, 18 by 10 by 7 inches, was broken lengthwise the first winter after being placed in the beach mud. The following winter an incipient fracture developed which was extended during the third winter so as to again split the stone.

Small boulders embedded in clay 75 feet from the lake, where surface drainage was fair, remained unbroken for several years until conditions favorable for frost-splitting occurred and then several were cracked. Brick and slate embedded in soil remained unchanged for several years in South Carolina but a single freeze, coming when the ground had been thoroughly saturated by warm rain, caused extensive fracturing and disintegration.

A standard method of testing the weathering properties of

stone, brick and cement is to saturate the samples by submersion in water, after which they are removed and subjected to freezing temperatures. This process is repeated several times, the specimens being weighed after each cycle to determine the loss through disintegration. The writer has modified this test by surrounding the sample with insulating material, the upper surface being exposed to refrigeration while the lower part of the specimen is kept saturated with water. The apparatus is essentially the same as that used to freeze soils in open systems where water can enter or be expelled from the soil during the experiment (Taber, 1929, 1930a and 1930b). Blocks of stone, brick and cement, in open systems, require fewer cycles of freezing and thawing to bring about a given amount of disintegration than when they are tested by the old method.

DISCUSSION AND CONCLUSIONS

In the writer's experiments, coarse-textured soils frozen in a system open with respect to water did not heave because ice merely filled existing voids, the excess water resulting from volume change being expelled; but, when fine-grained soils were similarly frozen additional water was drawn into the soil to build up masses of ice, and the heaving greatly exceeded that which could be attributed to change in volume of the water frozen. In the latter case the pressure effects were due to growth of ice crystals, the pressure being exerted in the direction of crystal growth which is determined by the direction of cooling, except when resistance to growth is much greater in that direction than in others. When highly colloidal bentonitic clays were frozen the heaving was equivalent to the change in volume of the water frozen because water could not enter or leave the impermeable clay during the experiment. In nature, as previously stated (Taber, 1930b, p. 116), there is a gradation, and not a sharp demarcation, between open and closed systems.

Stones behave very much as soils when frozen under similar conditions. Coarse-textured stones, such as sandstones, are seldom fractured because some interstitial water is expelled by the growing ice crystals; but, in fine-grained limestone additional water can be supplied to growing ice crystals from the underlying wet soil if downward freezing is sufficiently slow. It must be slow since a dense-textured stone is highly resistant to rapid flow of water. The larger blocks and boulders of limestone are seldom cracked by frost action, partly because of

high resistance to the growth of a few small ice crystals, and partly because the resistance to the passage of water through the minute pore spaces increases with the distance it has to travel.

Boulders resting on soil, but not deeply embedded, cool rapidly because of the high percentage of their surface exposed, and too rapid downward freezing may prevent ice crystals from enlarging the space they occupy and causing rupture. If the voids are relatively large ice may form downward through these spaces expelling surplus water, but if the voids are sufficiently small the resistance to rapid movement of water may exceed its tensile strength, which in small columns is surprisingly high, consequently cutting off the supply of water to the ice crystals.

The freezing isotherm descends more slowly in clay where a larger amount of water must be frozen than it does in stone where only a little water is available. Therefore, ice crystals may grow in a cobble for some time before the flow of water from clay to embedded stone is stopped by freezing. As winter approaches soil water freezes long before lake water, for much heat must be removed from the large volume of lake water to reduce the temperature at the surface to the freezing point. Lakes, therefore, tend to retard the freezing of mud and clay at, or close to, lake level. As the water is lowered in the fall the mud in which cobbles are embedded is saturated with water at approximately the temperature of water along the lake shore.

Limestone cobbles resting on gravel are seldom fractured by frost action because (1) insufficient water is present in the cobble, or (2) water cannot enter the limestone to feed growing ice crystals. Good drainage makes it difficult to saturate a cobble that is above lake level, but this explanation would not apply to cobbles that are partly submerged. Laboratory experiments (Taber, 1930b, p. 122) show that water occupying very small voids in fine-grained soils may be undercooled in the immediate vicinity of ice crystals but this is not true of coarse-grained soils. Similarly, water in the minute voids of the limestone may remain unfrozen while the 0°C. isotherm descends below the cobble where water occupying the large voids in gravel is promptly frozen, thus cutting off all upward movement of water into the cobble.

Cobbles and boulders embedded in clay at a distance from



Plate 1. Angular beach cobbles at Farleys Point on Cayuga Lake, New York. Half of a well-rounded sandstone cobble is shown immediately in front of the frost-split boulder.

the lake seldom fracture except when freezing occurs after the clay has been thoroughly saturated by rain, melting snow, or the concentration of water near the surface as a result of freezing and thawing.

Limestone cobbles and boulders on beaches underlain with fine mud are more or less angular because they are being ruptured by frost action faster than the fragments can be rounded by abrasion. The other types of rock present are much less susceptible to frost-splitting and therefore are mostly well rounded. On beaches with thick gravel deposits conditions are unfavorable for frost-splitting, and, therefore, cobbles of all rock types become well rounded. Recognizable fragments of shale are seldom present in the boulder clay or on the beaches, except where shale beds are exposed. Because of its cleavage and texture it is easily broken and disintegrated by frost action.

Extremely low temperatures are not required for the intensive splitting and disintegration of rock by frost action. A temperature of a few degrees below 0°C. is sufficient if the rock is fine grained and permeable, and if conditions permit the maintenance of saturation during freezing. In the absence of these conditions frequency of the freezing cycle is of little importance. Writers in the field of frost action have rather generally overlooked the fact that the growth of ice crystals in soils and rocks, with the development of pressure, is controlled by not one but by several factors, including size of pore spaces, size of particles, permeability, resistance to the enlargement of voids, rate of cooling and the availability of water. Resistance to crystal growth is generally greater in rock than in soil, and less uniformly distributed. Therefore location of fractures in rock often occurs along bedding planes and other loci of weakness. Thin tabular specimens of limestone are usually broken in a direction parallel to the smallest diameter. The principles developed in this paper have important engineering applications.

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DEVONIAN MICROFOSSILS, ANDREWS COUNTY, TEXAS

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ABSTRACT. A fossiliferous interval containing conodonts and questionable trochiliscids (Charophyta) from the lowest Devonian rocks of the Three-Bar field, Andrews County, Texas, is interpreted as a stratigraphic admixture of Devonian age. This is evidence indicating a Devonian age for the pay zone of the Three-Bar field.

CONODONTS and questionable trochiliscids (charophyte oogonia) occur in a thin, glauconitic sandstone at the base of the Devonian chert in the Three-Bar field, southwestern Andrews County, Texas. These fossils were first recognized in cuttings from depths of 8470 to 8480 feet in the Stanolind Oil and Gas Company's University No. 2 "AG". Larger quantities of fossiliferous material, obtained subsequently by diamond coring in the Stanolind Oil and Gas Company's University No. 4 "AJ", permitted a more thorough study of the fossils, which disclosed important evidence regarding the age of the pay zone of the Three-Bar field.

The Stanolind Oil and Gas Company's University No. 4 "AJ" is located 660 feet from the north and west lines of section 9, block 11, University Lands Survey, Andrews County, Texas. The description of the core recovered from depths of 8281 to 8286 feet is as follows:

Devonian	Feet	Inches
Smoky-gray, dense, vitreous chert with irregular masses of buff chalky chert	0	7.75
Green, glauconitic sandstone; interstices filled with iron sulfides, calcite, and pale green clay. Contains conodonts, conical fish teeth or scales, and tentatively identified internal molds of trochiliscids	0	1.25
Silurian		
Pale gray to green shaly limestone ..	4	0
Total depth 8286 feet.		

When the glauconitic sandstone from the base of the Devonian was immersed in water and boiled, it disintegrated and the microfossils were freed. The fossils were concentrated by

hand-picking with a small moist brush under a wide-field binocular microscope. All the fossils are amber-colored and the tentatively identified trochiliscids are soluble in acetic acid.

The general geographic and stratigraphic setting of the fossiliferous sandstone is shown in figures 1 and 2. It is immediately below the pay zone of the Three-Bar field and above a gray to green shaly limestone assigned to the Silurian on the basis of lithology and local usage. The fossils are illustrated on plate 1 and are listed as follows:

Conodonts

Icriodus expansus Branson and Mehl (platform)

Icriodus sp. (platform)

Oistodus sp. (simple cone)

Acontiodus sp. (simple cone)

Cordylodus sp. (simple cone)

Fish Remains

Small, low, conical fish teeth or scales.

Algae (Charophyta)

Questionable internal molds of trochiliscid oogonia.

Ninety per cent of the specimens found belong to the conodont genus *Icriodus*. Slightly less than 10 per cent of the specimens are questionable trochiliscids and a minor number are simple cone conodonts and low, conical fish teeth or scales. The simple cone conodonts are fragmentary and show evidence of abrasion. The low, conical fish teeth possess a distinct layer of enamel on their exterior.

The interpretation of the age of these fossils is based mainly on conodonts. *Icriodus expansus* Branson and Mehl is recorded from strata of Middle and Upper Devonian in the United States and the stratigraphic range of the genus *Icriodus* is recognized as being Middle and Upper Devonian (Branson and Mehl, 1938, pp. 156-161). A gap occurs in the knowledge of conodont faunas in the Lower Devonian because none have been described from that part of the system. The possibility that *Icriodus* may range into Lower Devonian, therefore, cannot be completely eliminated. The forms illustrated here are not similar to the genus *Icriodina*, which occurs in the Silurian of Kentucky (Branson and Branson, 1947, pp. 550-551).

The simple cone conodonts are interpreted as Silurian or Ordovician forms, reworked, and included in the glauconitic sandstone. There were ample source beds of Silurian or Ordo-

vician age to supply these reworked specimens. The low, conical fish teeth or scales are not known to have any value as age indicators.

The tentatively identified internal molds of trochiliscids are important in that trochiliscids are known only from the Middle and Upper Devonian and Lower Mississippian beds in the United States (Peck, 1934, p. 97). Their lowest stratigraphic occurrence is near the base of the Middle Devonian. However, trochiliscids are like conodonts, in that Lower Devonian occurrences are not known but the possibility of their existence in that part of the system cannot be ruled out.

The specimens shown on plate 1, figures 1-6, compare favor-

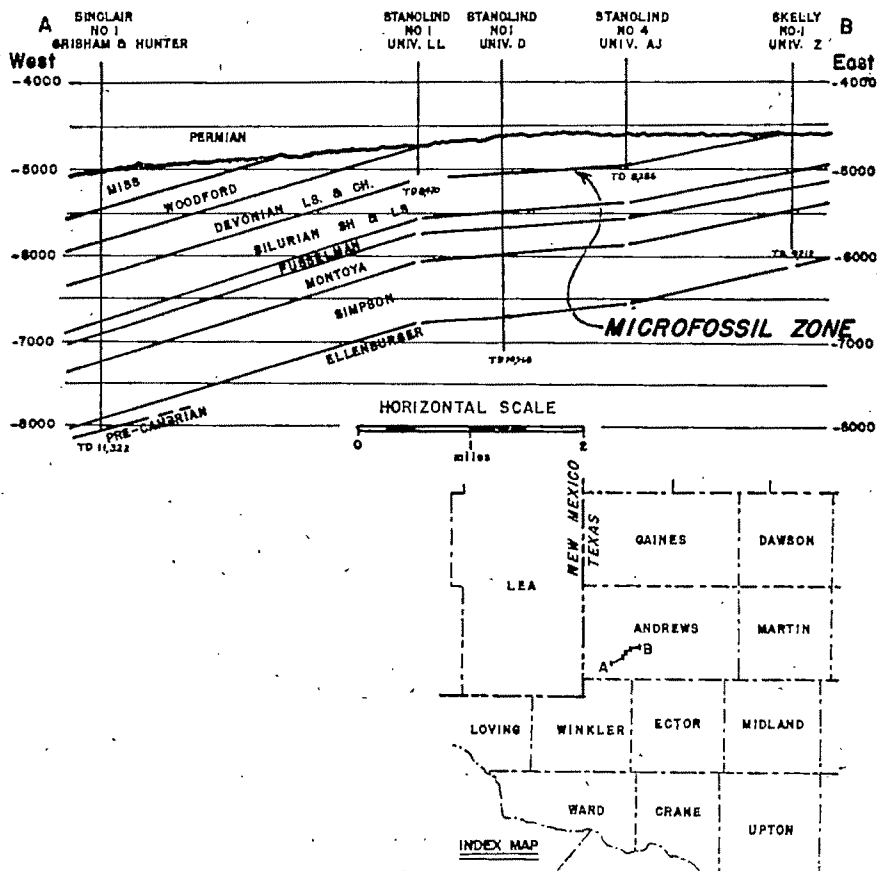


Figure 1. Geographic and stratigraphic setting of the Devonian microfossils.

ably with Peck's (1984, plate 12, figures 1-8) illustrations of internal molds in all respects except size: Peck's specimens are approximately three times as large. After examining the Three-Bar specimens, Peck wrote that they "do look like the internal molds of trochiliscids that I figured some time ago. I compared your material with the figured material and the resemblance except for size is remarkably close. The material I figured was from the Bushberg and the Devonian trochiliscids are much smaller. The size differential should not mean much. My means of identification of the material I figured was association and inference. The material you sent is unquestionably organic and I would not know where else to place it. At the same time, I could not possibly prove the material to be internal molds of trochiliscids" (personal communication, January 3, 1950).

In summary, the data and interpretations made above show this assemblage of microfossils to be a stratigraphic admixture of Devonian age. Silurian or Ordovician simple cone conodonts

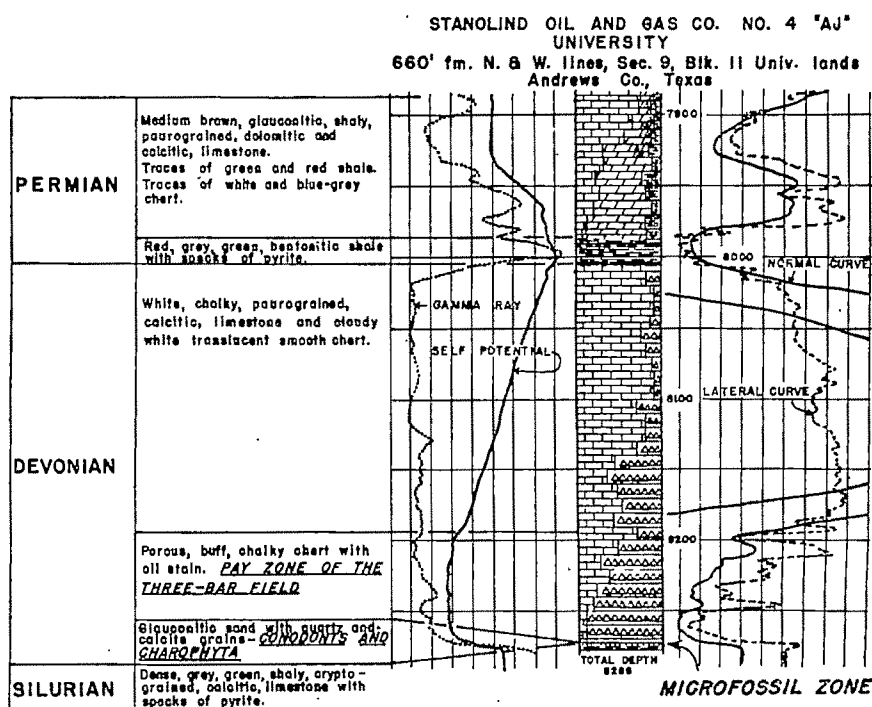


Figure 2. Detail of Stanolind well No. 4 (see fig. 1).

have been reworked and deposited in a basal sandstone containing Devonian conodonts and trochiliscids. Correlations with other faunas and floras in the United States indicate an age of Middle and Upper Devonian. However, a Lower Devonian age cannot be ruled out because of the lack of knowledge concerning Lower Devonian conodonts and trochiliscids. In any case, the interpretation given is evidence for assigning a Devonian age to the Three-Bar pay zone, which is immediately above the fossiliferous sandstone.

Acknowledgment is made to The Stanolind Oil and Gas Company for permission to publish the report; to R. E. Peck for examining the trochiliscids and for permission to quote his personal communication; to Mrs. Alberta Early for picking the specimens; and to A. H. Deen, R. K. DeFord, and J. T. Lonsdale for suggestions and criticisms of the manuscript. The photographs of the fossils were made with the financial aid of grant number 276 of the University of Texas Research Institute. The figured specimens are deposited in the paleontological collection of the University of Texas Bureau of Economic Geology.

Explanation of plate 1

All figures magnified 80x

All specimens from the Stanolind Oil and Gas Company's University No. 4 "AJ", southwestern Andrews County, Texas, at depths from 8281 to 8282 feet.

Figures 1-7. Questionable internal molds of trochiliscids (Charophyte oogonia). University of Texas Bureau of Economic Geol. No. 19293.

Figures 8-13. Unidentified fish teeth or scales. University of Texas Bureau of Economic Geol. No. 19294.

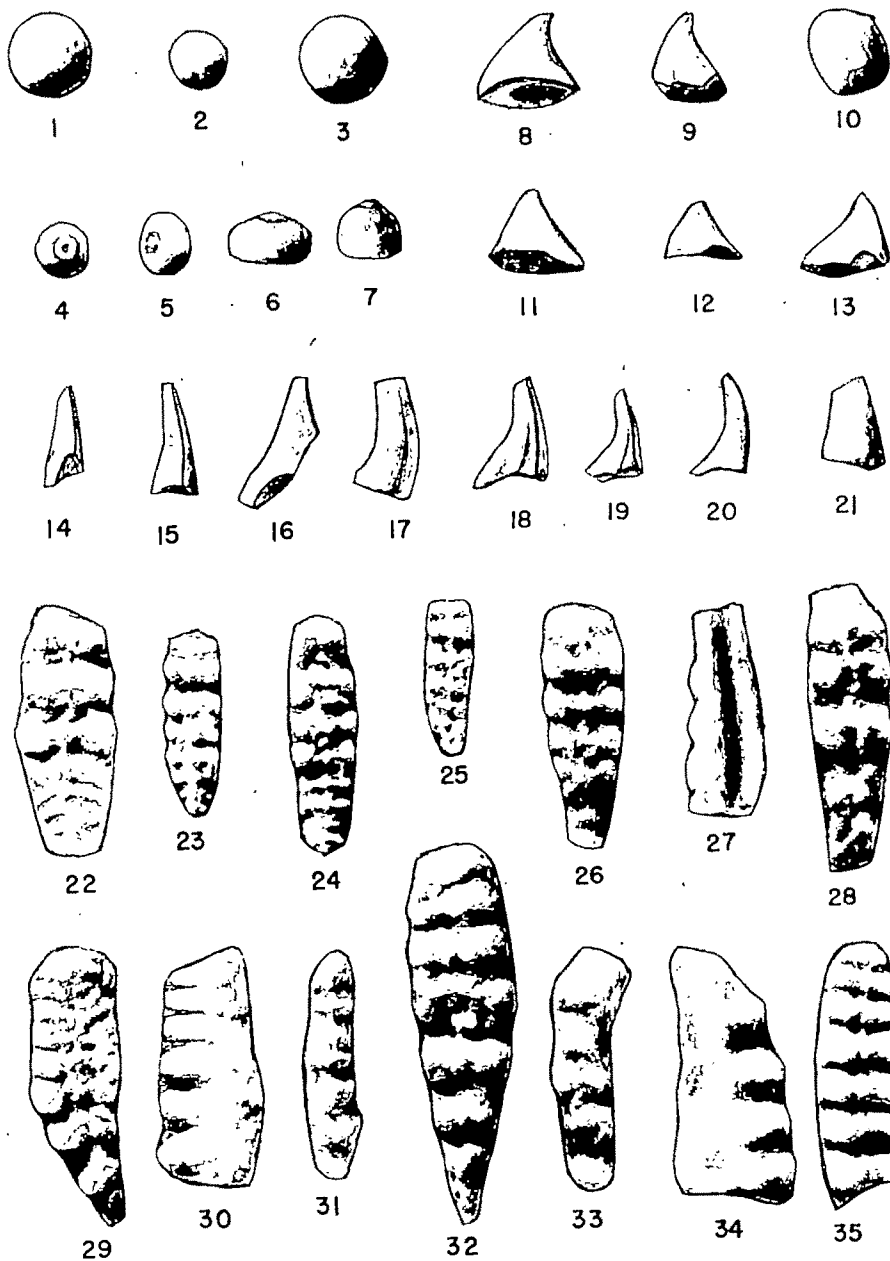
Figures 14-15. *Acontiodus* sp. University of Texas Bureau of Economic Geol. Nos. 19295, 19296.

Figures 16, 17, 21. *Oistodus* sp. University of Texas Bureau of Economic Geol. Nos. 19297, 19298, 19299.

Figures 18-20. *Cordylodus* sp. University of Texas Bureau of Economic Geol. Nos. 19300, 19301, 19302.

Figures 22-28, 31, 33. *Ieriodus* sp. University of Texas Bureau of Economic Geol. Nos. 19303 to 19311.

Figures 29, 30, 32, 34, 35. *Ieriodus expansus* Branson and Mehl, University of Texas Bureau of Economic Geol. Nos. 19312 to 19316.



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EQUILIBRIUM THEORY OF EROSIONAL SLOPES APPROACHED BY FREQUENCY DISTRIBUTION ANALYSIS

ARTHUR N. STRAHLER

PART II

SIGNIFICANCE TESTS APPLIED TO SLOPE PROBLEMS IN THE
VERDUGO AND SAN RAFAEL HILLS, CALIFORNIA

Introduction—Studies of the significance of differences in sample means have applications in the attack upon a number of fundamental geomorphic problems involving factors which affect equilibrium of graded slopes. Data collected in the Verdugo and San Rafael Hills, Los Angeles County, California, have been examined with a view to determining (1) if differences in underlying rock type are associated with differences in slope angles, (2) if differences in directional exposure to sunlight and other meteorological factors produce differences in slope angles, and (3) if slopes decline in angle when left to weathering and erosion processes not accompanied by basal erosion and removal.

Description of the Area.—For initial research three small areas in the Verdugo and San Rafael Hills were studied (figure 10). These lie in the southern side of a single NW-SE trending Figure 10.

Coast Range block of moderate relief (Miller, 1934). Conditions of climate, vegetation, relief and tectonic history are essentially the same throughout, but lithologic factors are not. The easternmost area is underlain by a relatively homogeneous mass of Wilson diorite; the western two areas by the metasediments and small intrusive bodies comprising the San Gabriel formation. Despite marked variations in bedrock composition and structure in the latter formation, the entire southern side of this range appears homogeneous in topographic aspect.

The field work was concentrated upon measuring slope angles in several categories, in measuring and plotting detailed topographic profiles from ravine floors to divides, and in determining the number and location of the smallest discrete channels of the drainage network. Information was plotted on photostatically enlarged copies of the U. S. Geological Survey

topographic maps on a scale of 1:24,000 corrected on the basis of air photograph study and field inspection (fig. 11).

Topography.—Mountain topography of the Verdugo and San Rafael Hills is in a mature stage of development. The drainage pattern is roughly dendritic, although the predominant trend of streams is southwesterly, from the major divide in which the streams head, to the sloping fan surfaces which encroach from the south upon the ragged foothill belt of the mountain base. Although there are many irregularities of bed-rock composition and structure, these seem to have rather minor influences upon the placement of minor streams and divides.

Slopes are steep (plate 1), with a tendency to straightness of profile (figs. 1 and 12). Divides tend to be smoothly rounded throughout, a form emphasized by the fact that firebreaks are made and maintained by bulldozer along the major divides. Serrate crests and craggy peaks, often seen in desert moun-

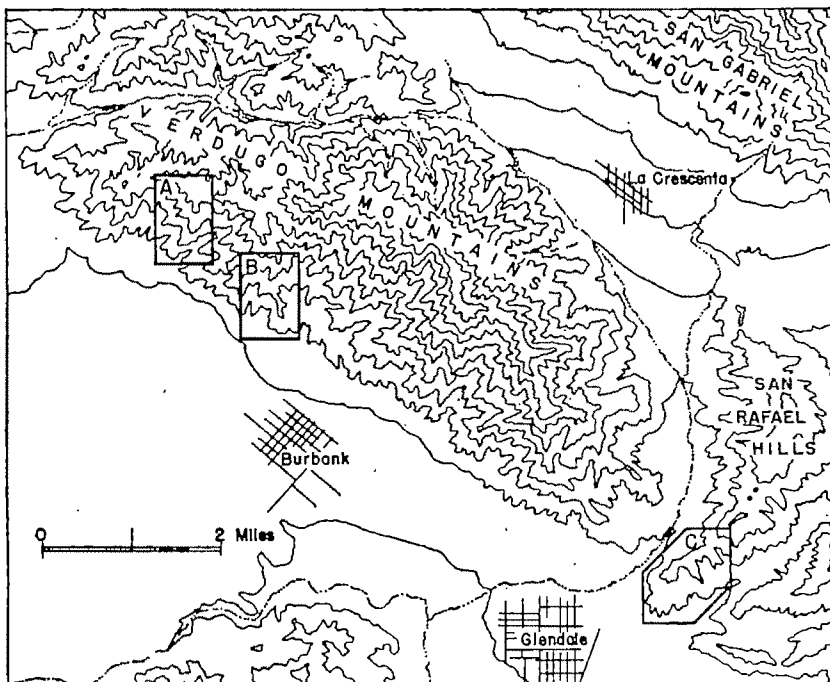


Fig. 10. Outline map of Verdugo and San Rafael Hills, Los Angeles County, California.

tain ranges and glaciated mountains are absent here. Relief is not great, despite the steep slopes. The areas studied have less than 1000 feet total relief while most slope profiles measured in the field have less than 100 feet of difference in elevation from divide to channel.

Ravines may be subdivided into two classes: (1) The smaller ravines and the upper ends of the larger ones are V-shaped in transverse profile. The enclosing walls have slopes in the range 40° to 45° for the most part. The stream channel, dry most of the time, is narrow and is cut in bedrock. Locally, however,

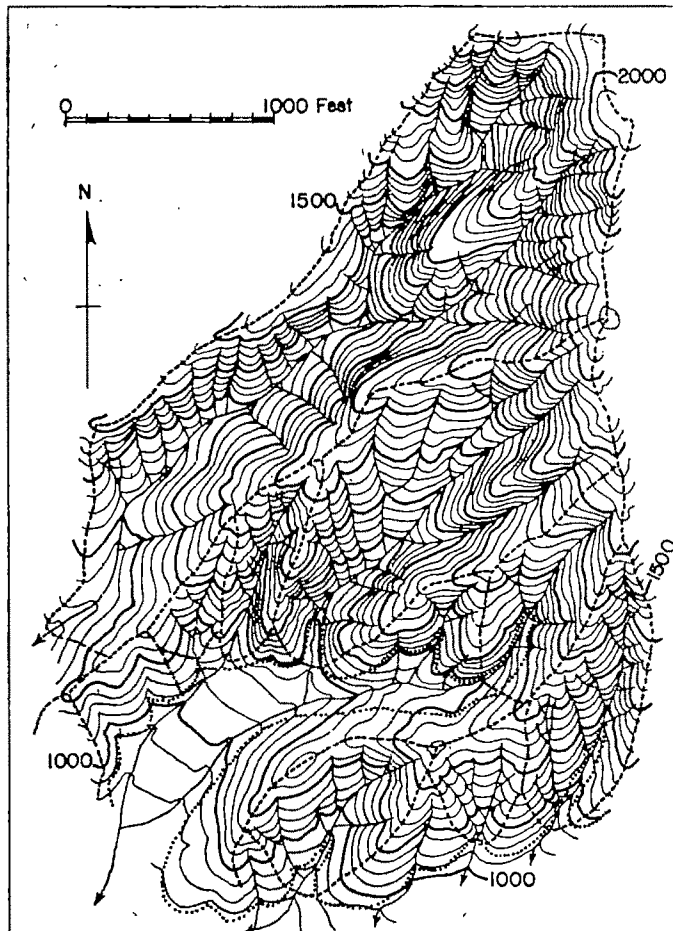


Fig. 11. Detailed map of Kline Canyon area, Verdugo Hills, Calif. (area A of figure 10.) Enlargement of U. S. G. S. map, 1:81,680, corrected in field.

the channel is choked with debris which has slid, rolled or flowed from the steep walls. (2) The lower courses of most of the larger canyons are graded and have a flat alluvial floor ranging from a few feet to one or two hundred feet wide. To what extent the flat is due to lateral corrasion in bedrock, rather than to alluviation by flood- and mud-flow of a formerly V-shaped valley is not easily determined. In the areas studied, a period of recent channel trenching showed alluvial and mud-flow fill. Streams strongly impinge on the base of the steep canyon walls, undercutting the bedrock. Where the stream has temporarily moved away from the slope base steep cones of talus have been built, causing a smoothed, concave-up basal slope of accumulation to be present.

Ravine heads are steep-walled, funnel-like amphitheaters which may be termed "hoppers" because their converging slopes feed detritus into the uppermost end of the stream channel. Hopper walls tend to be nearly straight in profile and to make the form of an inverted part-cone. Most hopper walls are very steep, above 45° in angle. Evidences of rolling and sliding of weathered rock are conspicuous. Bedrock exposure comprises from one-third to three-fourths of the hopper walls. Locally a layer or lens of resistant rock may produce a nearly vertical cliff, but for the most part the rock surfaces conform closely with the straight hopper walls.

Some hopper walls intersect the broadly rounded divide with a sharp, clearly defined break in slope, indicating the rapid expansion of the steep hopper slopes by rapid mass movement into a more stable profile determined by slower processes of creep and rain-wash. Elsewhere the hopper walls merge smoothly into the rounded divide profile and suggest a more nearly balanced slope condition.

The lateral slopes which extend from divide to ravine bottom are characteristically straight in profile for a considerable part of their length (fig. 12). At the upper end the profile merges smoothly into the curve of the divide; at the lower end the straight profile reaches to the ravine floor. In some ravines a composite profile was found, having a lower, or inner, segment steeper than that above it. This was interpreted as the result of a recent epicycle of accelerated erosion locally affecting some of the canyons.

Between-Area Differences in Slope.—Significance of dif-

ferences in means of three areas was examined for the purpose of determining a possible influence of bedrock on slope. Areas A (Kline Canyon area) and B (Stough Park area) are both underlain by the San Gabriel formation whereas area C (San Rafael Hills) is underlain by the Wilson diorite. Should the means of the first two areas prove to be similar, but to differ significantly from the third, the difference may possibly be due to rock type. Should the results fail to show any significant differences, one might conclude that these particular varieties in bedrock have no noticeable influence. Should the first two areas, both in the same type of rock, differ significantly, but one of them to be the same as the third, we might conclude that factors other than rock type influence slope more strongly.

Histograms of three frequency distributions, one from each area are shown in figure 6. In an earlier section on general distribution characteristics of slopes an analysis of significant skewness and kurtosis was discussed (tables 1, 2). Differences

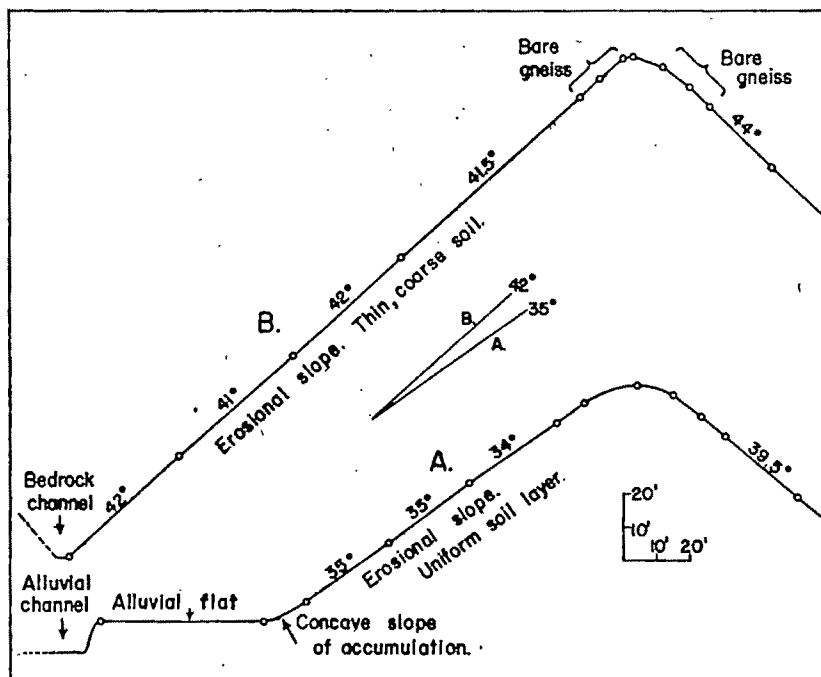


Fig. 12. Surveyed profiles in Verdugo Hills, California. Profile A, representing the type in sample A of figure 14, has escaped basal cutting for a long time. Profile B, representing the type in sample B of figure 14, is being actively corraded at the base.

in sample size are largely the consequence of the prevailing conditions of vegetation at the time of the field work. Area A had been recently burned over and presented an ideal condition for slope work. Area B had a light cover of shrubs following recent burns. Area C was densely overgrown with a chaparral of many years' development.

Tables 4, 5, and 6 give the essential data for the between-area analysis. Tests were made for significance of differences in estimated standard deviations and means.¹ Tests of sig-

TABLE 4

Data used in determinations of significance of differences in standard deviations and arithmetic means (tables 5 and 6.).

DETERMINATIONS	Area A	Area B	Area C
N Number of observations in sample	171	89	26
$\bar{X}$ Arithmetic mean of sample	44.825°	42.084°	42.173°
σ Standard deviation of sample	3.257°	2.522°	2.780°
s^2 Unbiased estimate of population variance	10.669°	6.433°	8.039°
$s^2 = \frac{N}{N-1} \sigma^2$			

TABLE 5

Tests for significance of differences in standard deviations.

DETERMINATIONS	A and B	A and C	B and C
F (Ratio of larger s^2 to smaller s^2)	1.658	1.327	1.250
$F = \frac{s_1^2}{s_2^2}$			
n_1 (Degrees of freedom in Sample 1.)	170	170	25
n_2 (Degrees of freedom in Sample 2.)	88	25	88
P. (Ratio of area in two tails of F-distribution to area under entire curve.)	0.02	>.40	>.40
Is there a significant difference in standard deviations?	Yes (?)	No	No

TABLE 6

Tests for significance of differences in arithmetic means.

DETERMINATIONS	A and B	A and C	B and C
t Where $t = \frac{\bar{X}_1 - \bar{X}_2}{s \sqrt{\frac{1}{x_1} + \frac{1}{x_2}}}$	6.90	3.92	0.15
n Degrees of freedom	258	195	113
P Ratio of area in two tails of t distribution to area under entire curve	<.001	<.001	.80 to .90
Are the differences in means significant?	Yes	Yes	No

¹ Analysis was performed by Mr. Richard Ostheimer, Instructor in Statistics, Columbia University.

nificance of differences in estimated standard deviations were required by the differences between area A and the other two areas. As indicated in table 5 there is probably a significant difference between deviations of areas A and B, but not between A and C, or between B and C. Inasmuch as the level of significance in the first case is not minute, we cannot rule out the possibility that they are really not significantly different. Certainly any influence of difference in bedrock fails to show strongly in the estimated standard deviations.

Differences in means are treated in table 6. The results are clearcut in terms of probabilities and satisfactory significance levels. Whereas areas A and C, and areas A and B, are significantly different, the differences in B and C are definitely not significant, with a probability of 80 to 90 per cent that this difference or greater may be due to chance sampling variations alone. Because the two areas of similar rock differ significantly in slope, whereas two of the unlike areas do not differ significantly in slope, we may conclude that some factor (or factors) other than bedrock has a controlling influence on slope differences. These factors might be undetected differences in climate, vegetation, soils, geologic (tectonic) history, or sampling differences due to unintentional changes in sampling method. The conclusions are thus negative, even though clear, and serve to emphasize the complexity of the type of problem being treated.

A possible explanation for a lack of any strong bedrock influence may be the deep weathering of bedrock in this region. Decomposition due to alteration of feldspars and ferromagnesian minerals has proceeded to depths of tens of feet, so that highway grading in bedrock may be done with power shovels. Landforms are thus little influenced by differences in physical characteristics of the unaltered rock.

Influence of Differences in Exposure of Slopes.—Throughout the areas studied there is a marked difference in the appearance of slopes facing south through southeast to east and those facing north through northwest to west. This difference is obvious both in vegetation and soil. In the field one is apt to conclude that systematic differences in slope angle are also present because of the fact that one set of slopes affords better footing for climbing than the other. Whether

or not a slope angle difference actually exists is here investigated by the method of differences in sample means.

All of the areas studied are clothed in a chaparral vegetation representing the natural flora of the region as it develops in various stages following fire. Two distinct types of vegetation are recognizable; that on the drier south-facing slopes, and that on the relatively protected north-facing slopes.

On the south-facing slopes is a light growth, 3 to 5 feet high, termed *chamise-sage* by J. S. Horton (1941). On the south flank of the Verdugo and San Rafael Hills this consists largely of *Adenostema fasciculatum* (Chamise). There are in addition *Eriogonum fasciculatum* (Buckwheat), *Salvia mellifera* (Black sage), *Artemisia californica*, and *Yucca whipplei*. Chamise seems to have excluded almost all other plants except the yucca on foothill slopes which have escaped burning for many years. Slopes burned over recently (3 to 5 years ?) may consist of almost pure stands of *Eriogonum fasciculatum* or *Salvia mellifera* or a mixture of the two, interspersed with some yucca. *Rhus laurina* occurs throughout the chamise-sage areas, making conspicuous dense clumps 8 to 10 feet high and most commonly attaching to rocky parts of the steeper slopes. According to measurements by J. S. Horton (1941) in the San Dimas Experimental Forest, the average percentage of ground occupied by plants is only about 24 per cent, while 76 per cent is open ground. Although no measurements were taken within the areas studied by the writer, it seems likely that there is a similar proportion of open ground. Viewed from opposite hillsides a chamise-sage slope shows a considerable amount of exposed soil, weathered rock mantle, or bedrock.

In contrast with the chamise-sage association is the *chamise-chaparral* association (J. S. Horton, 1941) of north-facing slopes. This is a denser, higher growth, some 8 to 15 or 20 feet high, composed largely of stunted trees. Horton's measurements show that only about 52 per cent of open ground area is present. Viewed from a distance little or no bare ground may be visible. A considerable amount of litter, made up of dead leaves and twigs, is present. In the area studied by the writer, the chamise-chaparral contained such species as *Prunus ilicifolia*, *Rhamnus crocea*, *Quercus dumosa* and *Rhus integrifolia*, intermixed with chamise.

Protection of ground by both of these chaparral associations is considerable, but would appear to be much greater where the chamise-chaparral association is present. On the chamise-sage slopes individual plants catch considerable quantities of twigs and leaves on the up-slope side of the plant base. This in turn holds soil and rock particles, making a miniature terrace. When the slope is swept by fire, much of the debris is released to slide and roll downslope into the ravine bottoms where it accumulates in small talus cones. The bare ground between individual plants or clumps of plants is readily attacked by raindrop beat (splash erosion) and sheet-run-off, which in places has cut small rill channels several inches into the weathered rock mantle. In dry weather these grooves serve as chutes down which loosened particles roll or slide. The activities of rabbits, coyotes, deer and other animals which live in large numbers on chaparral slopes serve to release much fragmental rock and soil material throughout the long, dry Mediterranean summer.

Nature of the soil cover is likewise contrasted on the two types of slopes. The N-NW-W chamise-chaparral slopes commonly have a thick, dark-brown soil through which no bed-rock crops out. A maze of fine rootlets binds the surficial part of the soil together so that free sliding and rolling of particles is minimized. The thick soil is given readily to flowage movements; the scars typical of such movements are conspicuous on burned-over slopes. On the S-SE-E slopes with a light chamise-sage cover, soil is thin. Outcrops are numerous and make up a large portion of the surface area of slopes over 40° or 42° . In the absence of soil held by rootlets there is much free rolling and sliding of weathered rock particles. Both because of the greater proportion of outcrops and because of the greater amount of sliding of detrital fragments, these slopes give the impression of being the steeper. They are more difficult to ascend or descend on foot than the soil-covered slopes (where both are freshly burned over) because footing is poorer in the loose unstable detritus on S-SE-E slopes.

In order to determine if a true and systematic asymmetry does exist between the two sets of slopes, a test was set up using slope angles previously gathered without regard for the particular problem of asymmetry. All ravines having simple, opposed valley walls were used; eight in all. These

ranged in trend from N-S to ENE-WSW and showed contrasting slope conditions as previously described. In all cases the ravine was sharply V-shaped with a narrow stream channel occupying the bottom. Thus the deepening of the ravine would cause approximately equal basal corrasion of both valley walls. Due to the complexity of bedrock, which included metasediments and small intrusive bodies, it is not certain that control by rock structure and composition differences is absent. No such relationship suggested itself, however.

Fifty-two readings were analyzed from slopes facing in a westerly or northwesterly direction; 53 from slopes facing southerly or southeasterly. The equality in number of readings was wholly fortuitous, because all available readings were used and none arbitrarily discarded. In general the distribution of readings was even throughout and opposite sides of the same ravine received almost equal sampling.

Of the first group, facing W, NW or N, the arithmetic mean was 44.54° ; for the second group, facing S, SE or E, the arithmetic mean was 44.56° (fig. 13). Note that standard deviations differ markedly even though means are almost identical.

A test of significance of difference in means shows

$$\overline{\sigma}_{\bar{x}_1} - \bar{x}_2 = 0.631$$

$$\frac{x}{\sigma} = 0.03168$$

The area under the two tails of the normal curve is 97.2 per cent. Hence the probability of obtaining this great a difference in means or greater due to sampling variations alone would be about 97 out of 100, if samples were repeatedly drawn from a slope population uniform throughout. It is nevertheless possible that a true difference exists due to exposure but that the two samples happened to have almost identical means. If we take the observed difference, plus or minus 2.6 times the standard error of the difference of the means ($.02 \pm 2.6 \times 0.631$) and we state that the true difference lies somewhere in this range of values, then, if we regularly proceed according to such a rule, in the long run 99 per cent of the statements will be true.

This example serves as an illustration of the value of systematic quantitative measurement and testing in investigating

what seems upon casual field observation to be a difference in slope angles due to exposure to meteorological elements. The eye alone cannot detect significant small differences and may, on the other hand, be deceived into registering a slope difference where none exists.

Parallel versus Declining Slope Retreat.—A fundamental problem in geomorphology is whether slopes of a fluvially dissected landmass retreat in parallel planes accompanied by replacement with a set of lower basal slopes, as Penck (1924) has held, or whether they decline to progressively lower angles as the landmass relief is lowered, as Davis (1909, p. 268-269) has held.

Under the equilibrium theory, outlined in earlier pages, slopes maintain an equilibrium angle proportional to the channel gradients of the drainage system and are so adjusted as to permit a steady state to be maintained by the process of erosion and transportation under prevailing conditions of climate, vegetation, soils, bedrock and initial relief or stage. Thus both slopes and streams are graded. In any one small area where homogeneity prevails slopes tend to cluster about a mean value with relatively low dispersion. As the landmass is reduced

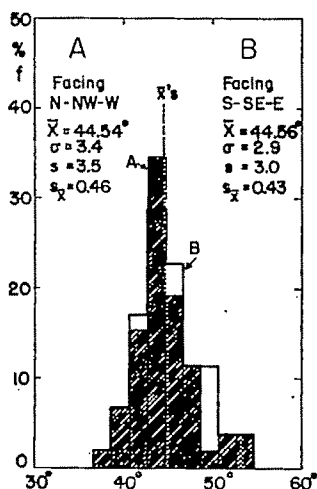


Fig. 13. Histograms of two samples superimposed for comparison. Sample A (cross-hatched) represents the more densely vegetated, sheltered northerly-facing slopes. Sample B (heavy line) represents thinly covered chamise slopes with southerly exposure. Means are almost identical, hence are indicated by one line.

both slopes and stream gradients are reduced, being slowly and continuously regraded to maintain approximate equilibrium. As the correlation of stream gradients with slopes (fig. 8) suggests, the decline of stream gradient is accompanied by slope reduction. This concept of maintenance of a steady state by slow readjustment is essentially Davis' concept of landmass development in the normal cycle.

Under the Penck (1924) theory of landmass development an initially steep slope or wall (*Böschung*) such as the valley wall of a youthful canyon, might be expected to retreat in successive parallel planes. So long as the stream is down-cutting at a constant rate, no other elements of slope would be present and uniform development would prevail. With diminishing rate of down-cutting by the stream there will begin to develop at the base of the steep slope a gentle slope (*Haldenhang*) which expands in area as the steep slope retreats from the valley axis. The *Haldenhang* is, in turn, replaced by still lower slopes (*Subhaldenhänge*). This concept fails to correlate stream gradients with slopes, as the theory of equilibrium forms in a steady state demands. Once formed, a steep slope (*Böschung*) would retreat at a constant angle regardless of changes of gradient of the associated stream.

In the Verdugo and San Rafael Hills the prevailing conditions are those of steep-walled, V-shaped canyons, or canyons with narrow alluvial valley flats. If the topography is developing by parallel slope retreat, as under the Penck theory, there might not yet be any development of *Haldenhänge* because of the rapid valley deepening and widening. It would thus be difficult to draw conclusions as to the correctness of these theories on the basis of general topographic aspect. There is, however, a possible means of determining the validity of Penck's assumption that a steep slope retreats in parallel planes once it has been formed and is no longer subject to direct basal stream action. At various places along the narrow alluvial flats in some of the canyons the stream is vigorously undercutting the bedrock at the slope base on one side, but has not recently been active on the opposite side, where there is an accumulation of soil and rock fragments in the form of talus or basal sheet-wash apron. The slope above this zone of accumulation has been free to waste back by processes of mass movement and sheet erosion, but without any removal or undercutting at the slope base. If retreat has been parallel, slopes of

this type should maintain a mean angle the same as for the slopes vigorously corraded at the base; if retreat has been of the declining type, these slopes should be significantly lower than the latter group.

During the field work measurements were made of erosional slopes which had basal accumulations of slopewash or talus and had, therefore, for a greater or lesser period of time, no vigorous corrasion at the base. In all 38 measurements of this class of slopes in the Kline Canyon area were made. These slopes were located among the slopes being actively corraded, of which the sample of 171 readings has already been described (sample E in figures 2, 3 and 4). The larger sample includes none of the smaller, but the two are intermixed as far as geographic distribution is concerned. Figure 14 shows the histograms of the two frequency distributions plotted on the same coordinates. The mean of the protected slopes is 38.2° ; that of the basally corraded slopes 44.8° , a difference of 6.6° . Estimated standard deviation of the first group (2.70°) is somewhat lower than the second (3.27°) but both are of the same general order of magnitude. It is obvious, in view of the significance levels obtained in previously described tests, that a difference in means of 6.6° is significant beyond doubt. A test shows that

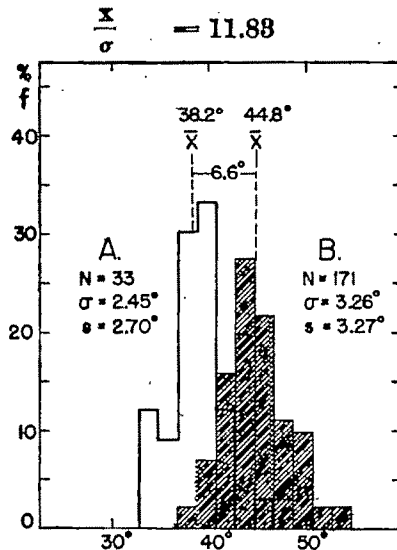


Fig. 14. Histograms of two samples superimposed for comparison. Sample A, protected slopes. Sample B, basally corraded slopes.

Tables of areas under parts of the normal curve fail to include this high a value. If the value were 5.0 the probabilities of obtaining this great difference or greater by chance variations in sampling from the same population would be on the order of one in one million.

We thus conclude that the slopes which have been protected from recent basal cutting have significantly lower angles. The statistical analysis does not explain this difference, but in view of the fact that conditions of climate, vegetation, soils, bed-rock, and tectonic history seem to be essentially the same for both samples it is concluded that the one group of slopes declined in angle during the period when only sheet-runoff, creep and other mass-wasting processes operated on the slope. Some suspicion, at least, is thus cast upon the Penck assumption of parallel retreat, while some support is given Davis' scheme of declining slopes.

Summary Statement.—The method of evaluating the significance of differences in sample means appears to have applications in the solution of fundamental problems of geomorphology. The method serves as a check upon the reliability of conclusions drawn from samples. In the three examples described above, the second and third illustrate opposite extremes of significance level which give considerable confidence to the investigator in drawing conclusions. The first case illustrates an inconsistent relationship among three sample means relative to a possible causative factor and points to control by other factors not under consideration.

Although the specific results of this investigation may prove of little consequence in the light of future studies, some value may come through increasing the range of techniques available in the attack upon basic geomorphic problems.

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COMMUNICATION

Evidence of the Taconic Sequence in the Vicinity of Lehigh River, Pennsylvania

In my paper on the Taconic sequence in Pennsylvania (Stose, 1946), the map of the Hamburg klippe, which embraced the known extent of the Taconic sequence in that area (fig. 2 of that paper) is shown as ending west of Lehigh River. Results of renewed study of the shale in the vicinity is presented here.

In the State Survey report on the geology of Northampton County, Penna. (B. L. Miller, *et al.*, 1939), seven inliers of limestone in the Martinsburg shale just east of Lehigh River are mapped. Ralph Miller (1937), who studied these limestones in detail, states (p. 108) "Two lines of evidence favor an Upper Cambrian age for these limestones. 1) There is a lithologic similarity to the known Upper Cambrian beds (Conococheague limestone) of the region. 2) In a number of different exposures, the fossil *Cryptozoon*, which elsewhere in the valley is restricted to the Upper Cambrian, has been found." He says also (p. 110) that these *Cryptozoons* "more closely resemble *Cryptozoon proliferum*," the fossil that occurs in the Upper Cambrian, than a form found in the Trenton limestone at Lake St. John, Quebec. Despite these facts, Ralph Miller could not bring himself to believe that the limestones were Upper Cambrian because the Martinsburg shale at the adjacent south side of the belt is underlain by the full thickness of Jacksonburg limestone and underlying Beekmantown limestone, both dipping gently north, which lie above the Upper Cambrian Conococheague limestone. He states (p. 109) "If unconformity be postulated, it would require that 600 feet of Jacksonburg and 1200 feet of Beekmantown thin out . . . in a horizontal distance of 600 feet. This seems impossible." He therefore concluded that the limestone inliers are local calcareous lenses in the Martinsburg shale, and they are so mapped in the County report (B. L. Miller, 1939).

In 1936 Miss Jonas and I examined the limestone inliers in the shale exposed on Catasauqua Creek north of Weaverville and along the road west through Seemsville to Kreidersville. We observed only one indistinct *Cryptozoon* in a quarry, and the limestone did not impress us as distinctly resembling the Conococheague limestone of the Great Valley. But if it contains *Cryptozoons* "in a number of different exposures," as reported by Miller, this fact cannot be ignored.

Red shale or other types of sedimentary beds known to be characteristic of the Taconic sequence were not observed in the vicinity of Seemsville, but such beds do occur 15 miles to the southwest

along the strike. The shale near Seemsville does have limestone inliers similar to those in shale at and north of Leesport and at many places farther west, where these limestones have been included in the Taconic sequence (Stose, 1946, p. 676). The limestone inliers in the vicinity of Seemsville, however, seem to be different in that they contain *Cryptosoon* that suggest Upper Cambrian age. The greatly disturbed character of the limestones, their brecciation, and the presence of many injected quartz stringers indicate much movement and possible thrusting. The limestone of the inliers, therefore, may be part of the floor on which the shale was deposited before it was thrust, and was thrust with the shale to its present position.

One mile north of Egypt, west of Lehigh River, the shale, with low north dip, is underlain by nearly horizontal thin-bedded fossiliferous limestone, crystalline limestone, shaly argillaceous limestone, and dolomite. The fossiliferous beds contain trilobites, which Ulrich identified as *Leiotidium* sp. (Stose and Jones, 1927, p. 512), and were referred by him to his "Upper Ozarkian" (lowermost Ordovician), somewhat higher than the *Cryptosoon* horizon of the Conococheague limestone ("Lower Ozarkian" of Ulrich). At the time this observation was published, the shale was regarded as Martinsburg and the underlying "Upper Ozarkian" beds were interpreted as evidence of an unconformity at the base of the Martinsburg. This shale is now regarded by the writer as part of the Taconic sequence and the underlying fossiliferous limestone is interpreted as part of the floor on which it was deposited before it was overthrust to its present position. These beds are in a triangular area west of a north-trending normal fault and north of an east-trending shear zone in the limestone, which is interpreted as the Taconic thrust (fig. 1). It lies just southwest of the Seemsville area of limestone inliers, and supports the interpretation that those limestones are part of the floor beneath the shale of the Taconic sequence that was thrust with it from the southeast.

The shale north of Egypt has no red shale, characteristic of the Taconic sequence, but 10 miles to the southwest, near Werleys Corner (fig. 1), red shale (Behre, 1988, plate 25), which is included by me in the lower part of the Taconic sequence, is in an anticline that plunges east beneath a thick series of sandy beds in which are "chip conglomerate," characteristic of the upper part of the Taconic sequence. All the shales and sandstones in the surrounding area, south of Shochary Ridge, are now tentatively classed by the writer as part of the Taconic sequence.

In my former paper (Stose, 1946, pp. 680-681 and fig. 3), I presented evidence of a thrust fault on the south side of Shochary Ridge whereby the shale of the Taconic sequence was thrust north over fossiliferous upper beds of the Martinsburg shale. This thrust

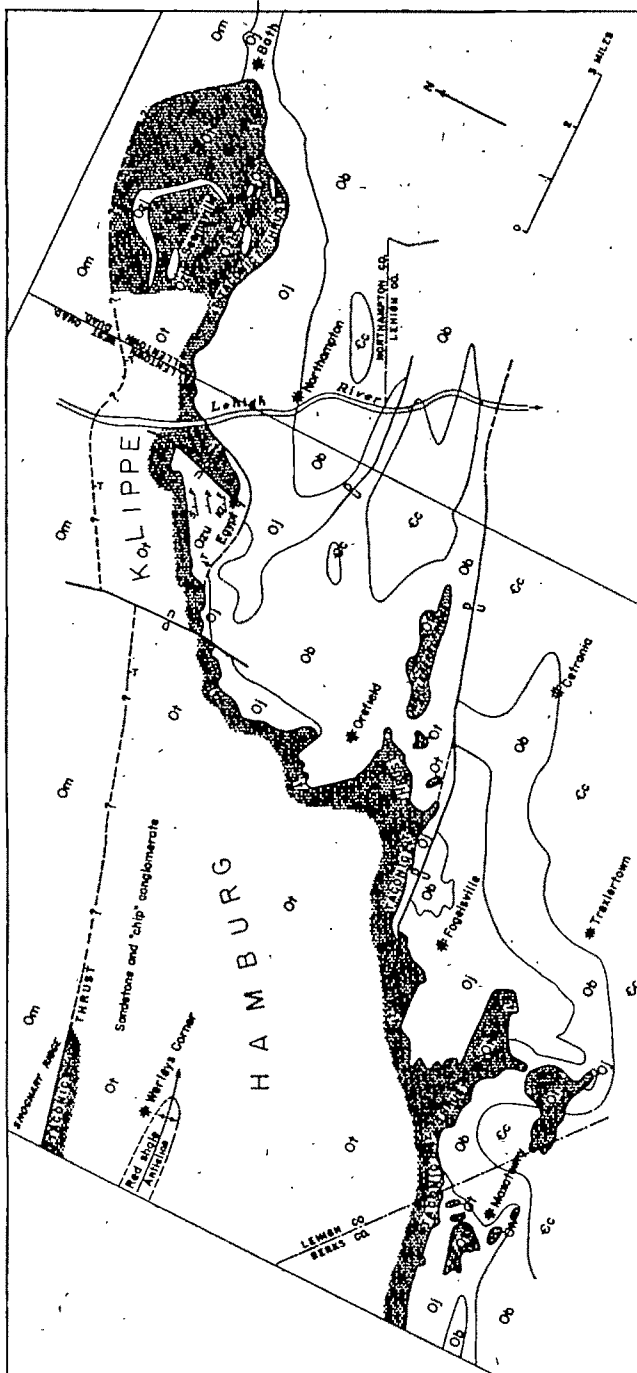


Figure 1. Tentative geological map of the vicinity of Lehigh River, Pa. From maps of Lehigh and Northampton Counties, B. L. Miller, modified and interpreted by G. W. Stose. A fault, tentatively labelled Taconic? thrust, is shown around the Hamburg klippe of Taconic rocks. Taconic rocks—Ot, shale and sandstones. OZu, limestone containing "Upper Ozarkian" trilobites. OZl, limestones containing *Cryptozoon*. Valley sequence—Om, Martinsburg shale. Oj, Jacksonburg limestone. Ob, Beekmantown limestone. Ec, Conococheague limestone.

passes eastward into the Allentown West quadrangle. As indicated on the map (fig. 1), I have included in the Taconic sequence the shale north of Egypt and the shale around Seemsville in which the limestone inliers occur; also all the shale and sandstones south and southeast of Shochary Ridge to the limestones of the Valley. In this area the irregular relation of the shale to the various older limestone formations has been very confusing because the shale was regarded as Martinsburg, but if the shale is overthrust, the irregular relations to the limestones can readily be explained, and confusion ceases to exist. The unconformable relation of the outlying shale area east of Maxatawny to the underlying Beekmantown and Conococheague limestones (B. L. Miller, 1941, geologic map) is made clear by regarding the shale as overthrust, as shown in figure 1. The shale of Huckleberry Ridge and other outlying shale areas east and west of Maxatawny, including the shale just described, are greatly disturbed and suggest overthrusting, and they are interpreted as klippen of the overthrust Taconic sequence.

The Taconic sequence of New York and New England, deposited in the eastern or Levis basin (Ruedemann, 1980, pp. 80-180), is composed largely of shale down to the Lower Ordovician Deep Kill shale, and the underlying Schaghticoke shale is tentatively regarded also of Lower Ordovician age. Beds of Upper Cambrian age and "Upper Ozarkian" of Ulrich are missing in the section. Shales, grits, and some limestones, that are lower in the section and extend down to the Nassau beds, are of Lower Cambrian age. Considering the distance of the Pennsylvania locality from the type area in New York, changes in the character and composition of the section along the strike might be expected, and the Ozarkian and Upper Cambrian, which are not represented in the Taconic section of New York, might be present in Pennsylvania and be represented by limestone and shale, of which the trilobite-bearing limestone near Egypt and the *Cryptozoon*-bearing limestone near Seemsville may be a part. Normanskill graptolites, typical of the Taconic sequence in New York, are present at many places in the Taconic sequence in Pennsylvania, and occur also in the Athens shale in the Shenandoah Valley of Virginia, where the shale is associated with fossiliferous limestones. Deep Kill graptolites, also characteristic of the Taconic sequence of New York, have been found at only one place in the Taconic sequence of Pennsylvania (Stose, 1980, p. 641; 1946, p. 674; 1950, p. 185) and are not known elsewhere in the Appalachians south of New York.

Conclusion.—All of the shale and sandstone that lie south and southeast of Shochary Ridge in the Allentown West quadrangle, extending eastward to Egypt and east of Lehigh River to Seemsville (fig. 1), are probably part of the Taconic sequence; the ir-

regular distribution of the limestone formations beneath the shale and its outliers around Maxatawny, Fogelsville, and Huckleberry Ridge accord with this interpretation. The limestone inliers in the shale around Seemsville containing *Cryptosoon*, and the fossiliferous limestone of "Upper Ozarkian" age beneath the shale near Egypt, may be part of the floor on which the shale of the Taconic sequence was deposited and were thrust with the shale to its present position.

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REVIEWS

Colloid Science, Vols. I and II; by A. E. ALEXANDER and P. JOHNSON. Pp. xx and viii, 887. Oxford and New York, 1949 (Oxford University Press, \$15.00).—Colloid Chemistry is a branch of Chemistry which deals with systems which are neither frankly homogeneous nor outspokenly heterogeneous. The subject touches so many fields that the table of contents, which summarizes the organization of the two volumes, covers 12 pages (this is about three and a half times as many pages as given to the index). The first volume consists of two parts: historical and general survey (5 chapters) and experimental methods and their theoretical basis. This latter part is again subdivided to treat systems as a whole (11 chapters) and the interface (8 chapters). The second volume is Part 3 of the whole work, and deals with the specific colloidal systems: sols, gels and pastes, foams, emulsions, colloidal electrolytes, clays and zeolites, proteins, polymers and membranes. An attempt is made in this part to discuss for each system methods of preparation or formation, structure in bulk and interface, stability, and the more important properties.

This work covers an extraordinarily wide field and, as it seems to this reader, does so in a clear style, with a large number of apt illustrations. It is a pleasure to read this work. In degree of difficulty the work falls between simple texts on colloid chemistry and monographs on very limited subjects. For this reason it can give a broad yet in some cases reasonably detailed treatment of colloid chemistry. This has been needed, and the book may very well become a useful text.

There are two features of the work which are somewhat disappointing. As noted above, the index is very short and is, indeed, quite inadequate. The orderly arrangement of the text and the extended table of contents redeem this situation a little. The other feature is the sparse documentation. References are given at the end of each chapter, but are not very many for a book of this kind.

The authors are to be congratulated on producing a work of such breadth. The two volumes will surely be valuable additions to the bookshelves of many workers in physical chemistry and in those earth sciences which draw on physical and colloid chemistry for support.

HAROLD G. CASSIDY

Albert Einstein: Philosopher-Scientist; edited by PAUL ARTHUR SCHILPP. Pp. xvi, 781. Evanston, Illinois, 1949. (The Library of Living Philosophers, Inc., \$8.50).—This book is the seventh of a series bearing the general title: *The Library of Living Philosophers*, each volume of which provides a group of interpretations of the work of a celebrated living philosopher by contemporary authorities, and includes the reply of the scholar in question to his commentators and

critics. Prefaced by an authoritative biographical sketch or, whenever possible, by an autobiography, each volume is concluded by a complete bibliography of the subject's writings. Such a plan has interesting possibilities and successful treatments of the work of such figures as Bertrand Russell, John Dewey, and Alfred North Whitehead have already appeared.

The man in the street accustomed by now to hear Albert Einstein acclaimed as an eminent mathematician and more particularly (and more accurately) as one of the greatest theoretical physicists of modern times, may well express surprise to find him here appearing in the guise of a philosopher. In the common view physicists are supposed to be suspicious of philosophers with their well-known penchant for explaining everything in terms of universal "systems," like idealism, materialism, etc., and their equally notorious inability to agree with each other on what really makes the world go round. On the other hand those physicists who have taken the trouble to examine the basic concepts of their science realize keenly how much a re-interpretation of such concepts can mean for future physical theorizing. It was to just such a process of searching analysis that Einstein subjected the ideas of space and time as previously employed in physics, and in so doing created the theory of relativity. If this sort of thing is philosophy, and the enormous interest which it has aroused among professional philosophers appears to indicate that it is, then Einstein certainly is entitled to rank as a philosopher as well as a scientist.

The general reader who approaches this book with the expectation of finding it another primer of relativity will be disappointed. The articles demand, in general, considerable background knowledge of modern physics and many of them dip pretty deeply into the abstractions of physical methodology. For physicists the introductory autobiographical sketch, which is entirely concerned with the genesis and development of Einstein's scientific views, will hold considerable interest, though the translation which accompanies the original German is scarcely adequate.

The twenty-five descriptive and critical essays which constitute the bulk of the volume divide themselves more or less naturally into three classes: (1) those descriptive of certain phases of Einstein's scientific achievements, (2) those relating to the philosophical implications of his work and particularly to his own definitely expressed methodological views, and (3) articles descriptive of certain theoretical developments suggested by or related to Einstein's relativity theory but actually independent of it and hence constituting original contributions. Typical of essays of the first class is the excellent article by Max Born on "Einstein's Statistical Theories." Examples of the second type are provided

by Niels Bohr's "Discussion with Einstein on Epistemological Problems in Atomic Physics," by Henry Margenau's "Einstein's Conception of Reality," and by P. W. Bridgman's "Einstein's Theories and the Operational Point of View." Finally the third class is well illustrated by E. A. Milne's "Gravitation without General Relativity," which is really a boiled-down exposition of Milne's own ingenious theory of kinematic relativity and its application to gravitation.

Though most of the essays stress adequately Einstein's great contribution to modern physical thought, many are rather critical of his methodological views. Of the controversial ones the most interesting to the reviewer is that of Bohr, which is a masterpiece of exposition and brings to the sharpest possible focus the fundamental disagreement between Einstein's views on reality and what constitutes a complete physical theory and those of the modern quantum physicist. In its essence it poses the old problem of the continuum versus the particle viewpoint in the development of physical theories, with Einstein maintaining his faith in the ultimate ability of the former to provide the best explanation of physical reality and with Bohr stressing the peculiar epistemological barrier erected against such faith by the existence of the quantum of action, which ironically enough, Einstein himself did so much to make a vital part of modern physics.

To the properly equipped student the reading of the essays in this volume cannot fail to be a very stimulating experience.

R. B. LINDSAY

Introduction to Statistical Mechanics; by RONALD W. GURNEY. Pp. vii, 268; 59 figs. New York, 1949 (McGraw-Hill Book Company, Inc., \$5.00).—One of the outstanding difficulties in grasping theoretical physics is the problem of separating the mathematics and the physical ideas. The subject of statistical mechanics carries with it all of these difficulties. Professor Gurney, already well known for books giving clarification of complicated subjects, has made a real contribution to the presentation of statistical mechanics. The first chapter, in which the basic concepts of the most probable distribution, and of temperature are introduced, should be read by everyone, whether he be already an expert or not. In the light of this simple approach the further mathematical development proceeds smoothly and the topics covered are easily understood.

The book must be regarded as elementary. There is no attempt to consider and contrast the various approaches to statistical mechanics. For example, the material necessary to consider the atomic nucleus from a statistical viewpoint is missing. However, as a basis for understanding chemical and solid state applications the treatment is excellent.

The first half of the book can be thought of as establishing a physically founded statistical method. This is then applied to dissociation equilibrium, solutions and alloys, expansion, condensation, lattice vibration, diatomic molecules, particles in electric fields and electrons in a metal. In every case the treatment is clear and gives a fresh insight.

One minor criticism is the back reference to numbered equations. In many cases it would aid the reader if the actual relation were repeated in place of the reference.

The book has already proved of value as a reference text for an undergraduate senior course. Student comments are favorable. It is clearly written and a pleasure to read. ERNEST C. POLLARD

Nuclear Radiation Physics; by R. E. LAPP and H. L. ANDREWS. Pp. xiv, 487. New York, 1948 (Prentice-Hall, Inc., \$4.50).—The enormous interest in nuclear physics since 1945 has been met with an astonishingly small response in text material. A striking exception to this unfortunate trend is the present well written book by Drs. Lapp and Andrews. It is intended to be read by anyone of scientific training, not necessarily physical in nature; and it includes a brief description of modern atomic physics, including x-rays, before the subject of nuclear physics itself is developed.

The topics covered in about four hundred pages include almost every development of interest up to 1948. For this reason it reads somewhat breathlessly. Thus the subject of beta decay, including Sargent diagrams, Fermi's E^2t relation, Konopinski-Uhlenbeck's modification, is contained in six pages. The compact treatment is excellently conceived and the authors are to be congratulated on the ability to present the essence so well. Nevertheless, from the point of view of the student the problem of assimilation may be difficult. With this one general criticism of density of content one can stop being critical. The diagrams and illustrations are excellent, ranging from simple explanatory diagrams to excellently chosen pictures of complex apparatus or of complex nuclear processes. Worked examples are provided to enable the student to become familiar with the rather surprising numbers of nuclear physics. Good problems are also provided in plentiful numbers.

Most important, the book has the flavor of modern nuclear physics, and is clearly written by authors who have experienced its rapid growth. It is a welcome addition to any bookshelf.

ERNEST C. POLLARD

Procedure in Taxonomy; including a reprint in translation of the Règles Internationales de la Nomenclature Zoologique (International Code of Zoological Nomenclature) with titles of and notes on the Opinions rendered to the present date (1907 to 1947);

by EDWARD T. SCHENK and JOHN H. McMASTERS; revised by A. MYRA KEEN and SIMON WILLIAM MULLER. Pp. 98. Stanford, 1948 (Stanford University Press, \$2.50).—The many systematists who have relied on this valuable little book for constant reference on matters related to the "International Rules" of nomenclature will welcome the augmented and modernized edition. The conspicuous additions are a brief chapter on the background and activities of the International Commission on Zoological Nomenclature, summaries of Opinions 124-188 and titles of Opinions 184-194. The sequence of chapters has been changed. Some useful new references have been added, and the text has been rather extensively transformed into more precise phrasing. The thorough index has, of course, been enlarged to cover the additions in the revision.

With the expectation that this edition will, like the first, be highly successful and again revised when reprinting becomes necessary, the reviewer must note the continued omission of a few points. (1) The definition of "taxonomy" needs to embrace the recognition and description of species, an aspect at least as important as nomenclature and "the ranking of the various categories." (2) The fact that the term "tribe" has been "variably employed" in the past does not remove it from justifiably wide modern usage for a very definite category in the classification of most groups of animals. As affinities become better and better known the need increases for a regular category between "subfamily" and "genus." (3) Important omissions in the list of types are "cotype" and "allotype." Regardless of the position individual authors may take on these terms, they are so commonly used in zoological taxonomic literature that it is essential that definitions be given in a reference work like this little book. It should also be emphasized in the definitions of "Primary types" that a specimen becomes a primary type only when so designated in a publication; this is a particularly important point for lectotypes and neotypes, for which loose practices are sometimes followed. (4) It is time for the problem of "genotype" *versus* "generotype" to be faced squarely, and the present authors should at least have mentioned the existence of the question. In genetics and systematics the term "genotype" is used for very different meanings. The increasingly wide overlap of these two disciplines makes it imperative that separate terms be used for the two concepts. "Genotype" appears to be firmly fixed and essential to geneticists. Furthermore, it cannot be derived from the combining form of "genus" (*gener-*) and should have been written "generotype" by systematists from the beginning. Such a spelling needs to be incorporated into the *Règles* and the term "genotype" abandoned for the type of a genus.

CHARLES L. REMINGTON

Earth Movements and Organic Evolution. Proceedings of Section L of the International Geological Congress, Report of the 18th Session, Great Britain, 1948. Pp. 59. London, 1950.—In the introduction to this symposium H. L. Hawkins (Great Britain), Chairman, sketches the problems of correlation between "orogenic spasms" of the earth and the speeding up of organic evolution. The subject is of perennial interest and was also a symposial topic at the last meeting of The Geological Society of America and associated societies. The papers contributed to this section of The International Geological Congress have their own merits, but they do not add up to a rounded discussion of the announced subject and most of them really have little or nothing to do with this subject. D. Andrusov (Czechoslovakia) summarizes the tectonic and sedimentational history of the western Carpathians and shows that this region had a long succession of radically changing environmental facies, reflected ecologically by its fossil faunas. L. V. Cepek (Czechoslovakia) discusses coal rifts or graben in western Bohemia and Moravia and demonstrates that the physical development of these depressions influenced the distribution of peat-bogs in them and is reflected in the quality, especially the ash content, of the resulting coals. A. Chavan (France) explains the appearance of tropical molluscs in the late Cretaceous and early Tertiary of northwestern Europe by migration and by increasing warmth of water following opening of the Atlantic basin by continental drift. R. C. Moore (U.S.A.) gives a rather detailed, largely tabular, summary of the evolution of the crinoids and suggests, without being explicit, that the history of that group has been strongly influenced by changes in lands and seaways. V. A. Obruchev (U.S.S.R.) is represented by an unimportant abstract. Finally, K. Zapletal (Czechoslovakia) maintains that major orogenic episodes, progressively displaced in various parts of the world, tend to localize major evolutionary events as to place and time. Although this last paper bears most directly on the problem announced by Dr. Hawkins, it is (to this reviewer) confused and unconvincing.

G. G. SIMPSON

Theory of Hearing; by ERNEST GLEN WEVER. Pp. xii, 484; frontispiece and 137 figs. New York, 1949 (John Wiley & Sons, Inc., \$6.00).—In the ten and more years since Stevens and Davis marshalled the facts known about the structure and function of the cochlea into their well known book, much has been learned about audition. Not only was practical knowledge greatly advanced by war-induced research but electrophysiological techniques were extended to single fibres of the cochlear nerve and to other parts of the auditory pathways including the cortical projections. At least 100 research papers from this period are cited in the bibliography of the present

volume which lists over 500. Consequently a book assessing the present status of this area of physiology and psychology is most welcome, particularly one written by a leading research man in the field. This welcome may, however, be somewhat tempered by the fact that Professor Wever has purposely written a book to support a particular theory of hearing, namely the so-called volley theory. Clearly, this of itself is not an indictment. However as this reader progressed through the work, he felt a mounting uneasiness at the continual hammering on this particular theory of cochlear function. The first third of the book, devoted to an excellent exegesis, cast in historical form, of the various theories of hearing, is most stimulating. The ideas are clear and the style effective. The illustrative material, mostly graphs, is good and the book is enlivened by reproductions of several masterly drawings by Max Brödel.

The larger part of the book then turns to the analysis, point by point, of the various data pertinent to hearing in terms of the volley theory. It will be recognized that this theory differs from the almost universally held hypothesis of cochlear physiology, i.e., some form of the place theory, by insisting that pitch recognition and associated phenomena are dependent mainly on the synchrony of stimulus frequency and nerve impulse frequency over a range of several octaves and partly so over 8-9 octaves, place only taking over above 4,000-5,000 cycles per second. Few would deny that such synchrony does occur at the lower end of the auditory spectrum, but few would find the evidence convincing that it is the cue for pitch. Perhaps we should rather look on the slant in Dr. Wever's book as an asset. A good controversy might well evoke just sufficient epinephrine secretion to fill in certain of the wide open gaps in our knowledge of hearing. In that case the volley theory, whether or not it turns out to be the most satisfactory one to account for the facts, will nevertheless have done valuable service.

TALBOT H. WATERMAN

An Index of Mineral Species and Varieties Arranged Chemically, with an alphabetical index of accepted mineral names and synonyms; by MAX H. HEY. Pp. xx, 609. London, 1950 (H.M. Stationery Office, Kingsway, W. C. 2; £1-10-0).—The chemically classified list provides a ready answer to anyone inquiring what minerals of a given qualitative chemical composition are known. The classification is based on the commonly accepted primary division of minerals by anions into oxides, sulphides, silicates, etc. followed by secondary subdivisions based upon the metals present. Cross-references are given in many cases where minerals contain several elements or radicals. The classification seems quite workable, as it has no doubt been proved by the author's personal experience at the British Museum. The alphabetical index of mineral names and synonyms is by

far the most complete modern index known to this reviewer; it occupies slightly more than half of the book. Its usefulness is greatly enhanced by references to the literature in which the respective names are defined. This book is clearly essential to any modern mineralogical library.

HORACE WINCHELL

Geophysical Survey of Southeastern Netherland; by L. U. DE SITTER and collaborators. Pp. 872; 73 figs., 2 halftone plates; 24 folded "annexes" (in separate container). Maastricht, 1949.—Following the invasion of The Netherlands by the Germans in May, 1940, the geological department of the University of Leyden had to abandon its program of field study in southern Europe, and instead began a concentrated attack on subsurface geology of the home country. Since the greater part of that country is blanketed with young sedimentary deposits, direct information at depth is obtained only in a few mining districts and in scattered areas where drill holes are concentrated. Parties were trained in use of the torsion balance, and 8684 stations were occupied. Maps and sections constructed from the data were destroyed by the retreating Germans in 1944; but, nothing daunted, the research team repeated the labor required to retrieve the loss.

Torsion balance results were supplemented by gravimeter data provided by the Geodetic Commission. Interpretation of these basic materials is expressed in a structure contour map, colored tectonic maps, and geologic structure sections. Where direct check by bore holes is possible, agreement is remarkably good. A pattern of steep faults that divide the bedrock into a mosaic of blocks is brought out particularly well by the gravimetric values. The project has large interest to geologists, as a demonstration of what may be accomplished in tracing known structural features that disappear under alluvial cover, and in mapping additional features by comparative appraisal of gravimetric anomalies.

Although the complete report, comprising 6 parts and an appendix, is printed in Dutch, condensed English translations that occupy the final 100 pages give adequate comprehension of the methods and the results. An alphabetical list of 131 references to pertinent literature adds to the value of the study.

CHESTER R. LONGWELL

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American Journal of Science

DECEMBER 1950

TETRAPODS OF THE PENNSYLVANIAN NODULES FROM MAZON CREEK, ILLINOIS

JOSEPH T. GREGORY

ABSTRACT. A revision of the Pennsylvanian amphibians and reptiles from Mazon Creek, Illinois, reveals that *Amphibamus* (including *Mio-batrachus* and *Mazonerpeton*) belongs to the rhachitomous labyrinthodont family Dissorophidae. *Microrpeton* (including *Humicrorpeton*) is the larva of a labyrinthodont possibly different from *Amphibamus*. *Sauroplesura*, a nectridian, is recorded for the first time from this locality. *Spondylorpeton*, an embolomere, the aistopod *Phlegethontia*, and the captorhinomorph reptile *Oephalerpeton* conclude the list of determinable genera. "*Mazonerpeton*" *costatum* is probably not a tetrapod and "*Amphibamus*" *thoracatus* is non-vertebrate.

The close similarity between Paleozoic vertebrate faunas of North America and Europe is attributed to rapid initial dispersal of newly evolved animals and cannot be regarded as evidence of a closer migration route than the Bering Strait land-bridge. Comparison with the diverse present-day amphibian and reptilian faunas of Europe and North America is misleading as these are composed, with few exceptions, of ancient families whose range was formerly far more extensive than at present. On the other hand, none of the faunal evidence opposes some more intimate connection; it is quite indeterminate as to the position of the migration route.

REMAINS of tetrapods are extremely scarce among the numerous fossils from the famous nodule beds at Mazon Creek, near Morris, Illinois, but the perfection of their preservation in comparison to approximately contemporary remains from cannel coals gives them unusual importance. Most authors who have studied these specimens have commented upon the remarkable preservation. Eye pigments, and according to Moodie, body color markings as well, impressions of body outline, and perfect molds of the bones filled with powdery kaolinite are characteristic; impressions of the filled intestines have been recovered in several specimens. The history of the discovery and description of these fossils has been told by Moodie (1912a, and 1916, pp. 12-15); Cope was first to describe amphibian remains from these nodules, but many of the specimens lay undescribed in various museums until Moodie undertook his researches upon the Carboniferous fauna which cul-

minated in the 1916 monograph. Subsequently certain of these specimens have been restudied by D. M. S. Watson (1940; see also Westoll, 1944) and the writer (Gregory, 1948); and Olson (1946) has reviewed the entire vertebrate fauna of this locality, pointing out needed revisions in Moodie's list. A critical re-examination of all known tetrapod specimens from the locality in the light of recent advances in knowledge of the relationships and structure of Paleozoic vertebrates form the basis for the present summary of the fauna.

Dr. David H. Dunkle has most kindly placed a number of undescribed specimens in the Lacoe Collection of the U. S. National Museum at my disposal for study and description. Dr. E. C. Olson has loaned types preserved in the Chicago Natural History Museum. I am indebted to Dr. E. H. Colbert and others of the staff of the American Museum of Natural History for the privilege of making comparisons with material from Linton, Ohio. Professor A. S. Romer of Harvard University has most kindly permitted me to read the manuscript of his paper on the "microsaurs." The illustrations have been prepared by Miss Shirley Glaser, staff artist of the Peabody Museum of Natural History. To all these I wish to express my gratitude for their invaluable assistance.

AGE AND CORRELATIONS

The Mazon Creek nodule beds are in the shales overlying the Morris, or No. 2 Coal which lies at the base of the Carbon-dale formation, middle Allegheny Series, at the base of the floral zone of *Pecopteris* and *Neuropteris flexuosa*. It is correlated with zone H of Dix in England and zone D of the late Westphalian of Germany. Thus it is somewhat earlier than the comparable faunas from Linton, Ohio and the "Gaskohle" of Nyrany, Bohemia, but may be nearly contemporary with that from the Jarrow Colliery, Kilkenny, Ireland. Further discussion of the correlation may be found in Westoll (1944, pp. 8-10) and Romer (1947, pp. 323-325).

Faunal list.

Class Amphibia

Subclass Apsidospondyli

Superorder Labyrinthodontia

Order Rhachitomi

Family Dissorhophidae

Amphibamus grandiceps Cope

= *Mazonerpeton longicaudatum*

Moodie

= *Miobatrachus romeri* Watson

Family incertae sedis

Micrerpeton caudatum Moodie

= *Eumicrerpeton parvum* Moodie

Order Embolomeri (?)

Family Cricotidae

Spondylrpeton spinatum Moodie¹

Subclass Lepospondyli

Order Nectridia

Family Urocordylidae

Sauropleura sp.

Lepospondyli ? incertae sedis

Order Aistopoda

Family Dolichosomidae

Phlegethontia mazonensis Gregory

Class Reptilia

Order Captorhina

Family Protothyrididae

Cephalerpeton ventriarmatum Moodie

Indeterminate specimens

Erierpeton branchialis Moodie

Erpetobrachium mazonensis Moodie

"*Mazonerpeton*" *costatum* Moodie

A comparison of the faunal lists for Mazon Creek given by Moodie and Olson with that above reveals a striking diversity of opinions about the relationships of the various forms. Moodie recognized 10 species of tetrapods, which he distributed among 8 genera and 5 families. Olson also recognized 10 species, but arranged them very differently. In the present summary only 6 genera and species are recognized, with 3 of the previously described forms listed provisionally as indeterminate. "*Amphibamus thoracatus*" Moodie is found to consist of plant impressions; *Erierpeton branchialis*, *Erpetobrachium mazonensis* and "*Mazonerpeton*" *costatum* are based upon nondiagnostic fragments. *Mazonerpeton longicaudatum* and *Miobatrachus romeri* are considered synonyms of *Amphibamus grandiceps*.

¹ Olson, 1946, p. 302, lists "*Spo. mazonensis* Moodie," an obvious lapsus.

ceps Cope. *Eumicrerpeton parvum* is synonymous with *Micrerpeton caudatum*. Two Orders, the Nectridia and Aistopoda, which have not previously been recognized in this assemblage, have been identified among hitherto undescribed specimens.

To those who would object to this drastic reduction in the nominal list of Coal Measures Amphibia, on the grounds that then as today, favorable habitats must have been teeming with batrachians many of which have left no trace, it must be emphasized that the Mazon Creek locality is a small area whose deposits indicate uniform conditions. The small sample of the fauna which is likely to be preserved at one spot would consist of several individuals of the more common forms, and perhaps a few of the less abundant or less aquatic types. It would fail to capture the closely related species which may have inhabited similar environments to the north, east, south, or west. At this locality, and at one time, the fauna would not be likely to contain more than one species of any genus. Therefore, it is closer to the truth to regard the morphological variation among obviously closely related forms from a single locality as an indication of the variability of the species rather than possible interspecific variation. Several specimens resemble the type of *Amphibamus grandiceps* so closely that their inclusion in that species is not likely to be seriously questioned. Less mature forms, however, depart considerably from the proportions of the typical specimens and frequently are insufficiently preserved to show crucial characters. Such larvae are, after all, indeterminate, and have been lumped as "branchiosaurs." Some of these small forms show features which are at least strongly suggestive of *Amphibamus*, and it is quite possible that *Micrerpeton* really consists of larvae of that species. That adults and larvae of the same species of labyrinthodont may occur together is demonstrated by the abundant series of growth stages of *Archegosaurus* from Lebach, the occurrence of *Melanerpeton* and *Diplovertebron* at Nyrany, and at other localities (some reviewed by Romer, 1939). There is no assurance that all the *Amphibamus* material is not immature; one can only trace its development up to the largest individuals preserved, whose size is comparable to modern small amphibians.

ENVIRONMENTAL IMPLICATIONS

Westoll (1944, p. 107) pointed out the frequent association of nectridians, aistopods, and haplolepid fishes in a facies

fauna which he regarded as indicative of stagnant shallow waters full of accumulating plant debris and lacking in oxygen. At that time the Mazon Creek occurrence of haplolepidids seemed an exception to this type of association which required special explanation; the subsequent discovery of both aistopods and nectridians at this locality brings the assemblage into line with the hypothesis. However, the Mazon Creek fauna differs from others of this facies in being preserved in shale instead of coal, and in the numerical predominance of labyrinthodonts instead of nectridians. As these shales immediately overlie the coal, they do not necessarily represent a greatly different environment from that under which coal accumulated. The profusion of coal-swamp plants indicates similar floral conditions. A slight increase in the amount of clay brought in by the streams might bring about the transition from coal to shale deposition without rendering the waters uninhabitable to the coal-swamp fauna.

In discussing *Phlegethontia* (1948b, pp. 652-654) I suggested that this aistopod may have been snake-like in habits, and not aquatic. The greater frequency of these animals in the cannel coals than elsewhere does not favor such an hypothesis. The scarcity of reptiles in these assemblages suggests that they were not members of the same association as the labyrinthodonts, nectridians, and fishes, but rather were inhabitants of the shores of the pools (or possibly trees). The relative infrequency of aistopods compared to nectridians at Linton might be explained on the same basis; at Mazon Creek, however, the former order is actually better represented, although no significance should be attached to the difference between such small numbers.

PALEOGEOGRAPHIC IMPLICATIONS OF THE COAL MEASURES FAUNA

Close resemblances between the Pennsylvanian vertebrate fauna of North America and that of Western Europe were first recognized by Cope (1868, p. 215). Advocates of both land bridges and drifting continents have cited them as supporting evidence for their theories (cf. Nopcsa, 1934, pp. 94-95). In comparing the common elements of the Mazon Creek and Linton faunas with those of Jarrow and Nyirany, one encounters an obstacle in the current nomenclature, which maintains generic distinctions between Pennsylvanian amphibians of North America and Europe with the sole exception of

Ophiderpeton. The family relationships between many of these animals is quite apparent, and 11 (50%) of the 22 tetrapod genera now recognized from Linton and Mazon Creek have closely related analogues at either Nyraný or Jarrow.² If the *Cochleosauridae* and *Dendrerpetontidae* are considered a single family for purposes of comparison, 10 (59 per cent) out of a total of 17 families of tetrapods known from the North American Pennsylvanian also occur in Europe. Two other American families, the *Zatrachyidae* and *Hylonomidae*, appear in the early Permian of Europe. Still another Superfamily of labyrinthodonts, the *Micropholoidea*, is represented in the two faunas by rather divergent families, the *Lysipterygiidae* and *Chenoprosopidae*.

These identical families and closely related genera form a larger proportion of the Pennsylvanian fauna than the common elements of the Recent amphibian and reptilian faunas of Europe and America. (According to Romer (1945b, p.436) only 24 per cent of the genera and 48 per cent of the families of these Classes which today inhabit Europe also occur in North America.) Still closer similarities existed between the early Permian faunas. Romer (1945b, pp. 434-440) has argued that the higher degree of similarity between these late Paleozoic vertebrate faunas than between Recent Amphibia and Reptilia of the two regions, points to a more readily traversible connection than that provided by the Cenozoic Bering Strait land bridge. In particular, he emphasized the presence of closely related or identical genera of recently developed and rapidly evolving paleoniscid fishes, rhachitomes, and lepospondyls which imply intimate continental connections. Westoll's (1944, pp. 109-110) analysis of the environmental implications of the aistopod-nectridian-haplolepid assemblage emphasized the importance of suitable habitats along the migration route, and led him to a similar conclusion; he argued that continental drift would bring the fossiliferous areas into closer proximity than a land bridge.

²This summary is based upon the following comparisons:

Spondylrpeton—*Diplovertebron*;
Leptorhactis—*Gaudrya*; *Branchosaurus*—*Cochleosaurus*;
Platyrhinops—*Mordax*; *Sauroplesura*—*Scotosaurus*;
Ctenoserpens—*Urocodon*; *Ophiderpeton* common to both;
Phlegethonia—*Dolichosoma*; *Tuditanus*—*Microbrachius* or *Hylolation*. Family assignments follow Romer, 1947.

It does not follow from the greater faunal similarity that the connection was more direct than the Cenozoic Siberian-Alaskan land bridge. Present-day dissimilarity between amphibians and reptiles of temperate North America and Europe is a direct result of the antiquity of these Families. Most of these animals were well established by Cretaceous times and many are known from the fossil record to have been more widely distributed in the early Cenozoic than at present. It is unnecessary to assume continuous or even frequent intercontinental migrations during the Cenozoic to account for their present distribution. With the exception of *Bufo*, *Hyla*, and *Rana*, all of which have species which are tolerant of cold (Darlington, 1948, p. 17), and which may recently have attained a circumboreal distribution, (*ibid*, p. 21), and possibly the emydid turtles (*ibid*, p. 23) the Recent herpetofaunas of the northern hemisphere are essentially relicts, made up of animals whose ranges have notably contracted since the early Cenozoic. Darlington (1948, p. 17) points out that salamanders form an ideal example of a relict distribution; snakes, lizards, crocodilians and turtles all show evidence of contracting range during the Cenozoic and the north temperate forms are mainly related to those in the adjacent tropical areas. Pelobatine frogs have a relict distribution analagous to salamanders; *Miopelodytes* Taylor (1941) from the Miocene of Nevada shows the former greater range of European genera of this Family. Differential extinction in Europe and America has brought about present-day diversity from a once more wide-spread and homogeneous fauna.

Mammals, on the other hand, were rapidly evolving during the Cenozoic, and new adaptive types repeatedly penetrated, in both directions, from one continent to the other, as Simpson (1947) has shown in great detail. It is worthy of note that the degree of resemblance between the early Eocene mammalian faunas of Eurasia (mainly Europe) and North America is of the same order of magnitude (42 per cent genera and 89 per cent of families in common) as between the Pennsylvanian amphibian-reptile faunas under discussion. In each case a relatively recent origin and rapid expansion of range of the groups in question is indicated, and the resemblances are greater than at subsequent periods after regional differentiation has set in.

A high degree of faunal resemblance between terrestrial and

freshwater vertebrates of two areas is not indicative of a long and close connection between the areas involved (a variety of the often refuted age and area hypothesis) but merely indicates that migration between the two areas is possible for the particular organisms under consideration. It is quite probable that animals which are rapidly evolving new adaptations may expand their range, within limits imposed by ecological factors and major geographic barriers, and spread throughout the available areas in negligible time geologically. The absence of competing types undoubtedly favors such rapid spread; and competition is an important limiting factor preventing the extension of range of genera now confined to Europe or North America.

Westoll's argument that the environmental requirements of haplolepid fishes and associated organisms were so specialized that the long migration route across the Bering Strait, or even across a North Atlantic land bridge would be a serious obstacle to dispersal is a more compelling argument for the drift hypothesis than mere faunal similarity. It is granted that close land connection between North America and Western Europe, such as provided by the drift hypothesis, would provide an easy migration route for these creatures; but their presence by no means proves the connection. Although present knowledge of Pennsylvanian paleogeography of Asia, in particular, is extremely scanty, the evidence which is available is not unfavorable to a suitable migration route somewhat along the lines of the present connection. Eardley (1949, pp. 664-670) shows persistent uplift and land areas extending northwestward from the central United States from Mississippian through Permian time, east of the Cordilleran seaways. This land area may at times have been continuous with a land mass which is thought to have lain north of the marine sediments of the Brooks Range in northern Alaska, and extended north of Siberia toward Europe (Eardley, 1948, p. 427, fig. 7). Such a land area would provide a path of migration between northern Asia and central North America. There are possibilities of persistent geosynclinal seas crossing this path, both at the American and European ends. During times when the seas withdrew from these areas, migration would be possible.

Data are even more scanty on the environmental conditions in the far northern parts of this route. Coals of Pennsylvanian

age are not found, but most of the sediments of this age thus far known in the north are marine; corals were well developed in the Mississippian seas at 69° North Latitude, and typical Arctocarboniferous plants occur with coal seams in early Mississippian at Cape Lisburne. It therefore does not seem unreasonable that at times during the Pennsylvanian suitable environments prevailed across what is now the Arctic Ocean for the migration of the coal swamp fishes and amphibians.

Land (and freshwater) animals may sometimes furnish evidence that certain geographical relationships are highly improbable, such as Cenozoic connections between Africa and South America; and they may also indicate that at some time a traversable connection was available. But it is doubtful whether the position of any migration route can be deduced from faunal evidence independent of geographical and geological considerations. The faunal similarities between Europe and North America in the Pennsylvanian indicate beyond doubt that a migration route traversable by freshwater fishes, amphibians, and small reptiles was available between these regions at that time, but afford no evidence about its position.

SYSTEMATIC REVISION

CLASS AMPHIBIA

Subclass Apsidospondyli

Superorder Labyrinthodontia

Order Rhachitomi

Family Dissorhophidae

Amphibamus grandiceps Cope

Cope, E. D., 1865, Proc. Acad. Nat. Sci. Philadelphia, 1865, 184-187; 1866, Geol. Surv. Ill. vol. 2, 135-141, 1 fig., plate 32, fig. 8.

Moodie, R. L., 1916, Carnegie Inst. Washington Publ. 238, 126-131, figs. 26-28, plate 4, figs. 5, 6; plate 3, fig. 7, plate 14, figs. 1, 2.

Watson, D. M. S., 1940, Trans. Roy. Soc. Edinburgh, 60, 195-198, fig. 1.

Mazonerpeton longicaudatum Moodie, 1912, Kansas Univ. Sci. Bull., 6, 337-341, plate 3, figs. 1, 2; plate 7, fig. 3; plate 10; 1916, 61-63, fig. 14a, plate 3, figs. 5, 6.

Miobatrachus romeri Watson, 1940, Trans. Roy. Soc. Edinburgh, 60, 198-208, figs. 2-10.

Type: Nearly complete skeleton figured by Cope, said by Moodie to have been destroyed. Neotype: Yale Peabody Museum No. 794, nearly complete skeleton in counterpart, figured by Moodie, 1916, figs. 26, 27, p. 4, and by Watson, 1940, fig. 1. A third specimen referred by Moodie (1916, plate 14) cannot now be located.

Type of Mazonerpeton: Yale Peabody Museum No. 795, incomplete skeleton in counterpart.

Type of Miobatrachus: Chicago Natural History Museum No. 2000, complete skeleton in counterpart.

The first amphibian to be found in the Mazon Creek nodules was described by Cope in 1865 as *Amphibamus grandiceps*. He first referred it to a new and distinct Order of Amphibia, the Xenorachia, which he considered intermediate between the Labyrinthodontia and Caudata; later (1875) he placed it in the Colosteidae along with *Sauropleura* and *Colosteus*. O. P. Hay described a second specimen in 1900 and pointed out that the ribs were long and slender, unlike those of typical branchiosaurs; he suggested relationship to *Hylonomus*. Moodie (1916, p. 127) concurred in this opinion, referring *Amphibamus* to the Microsauria, principally upon the character of the ribs. He erected a separate family for it and placed the small reptile *Cephalerpeton* in the same family. Romer (1930, p. 93) considered *Amphibamus* a branchiosaur and Watson (1940) referred it and the closely similar *Miobatrachus* to the Phyllospondyli but placed them in a separate family from the branchiosaurs. Romer (1945a, p. 591) followed Watson's suggestion of relationship to the frogs and placed these genera in the Salientia as a primitive Order Eoanura. Case (1946) separated *Amphibamus* and *Miobatrachus* in his classification, referring the former to the Microsauria on the basis of Moodie's description of the vertebrae and ribs, and followed Watson in referring the latter to the Phyllospondyli. The present study had its inception as an effort to resolve this problem by a re-study of the specimens.

It would be superfluous to redescribe the more perfect specimens of *Amphibamus* in detail after Watson's thorough account of its morphology. Discovery of both postparietals and horned tabulars (or supratemporals) in all extant specimens of the animal requires a revision of his reconstruction of the skull table, and some reconsideration of the relationships of the genus. Evidence for this will be set forth, and the diagnostic

characters of the several specimens will be reviewed to determine their relationship to one another and to the now lost type figured by Cope (1866, plate 32, fig. 8).

Characteristic features of the genus shown in the type figure include the large skull with truncate muzzle, wide inter-narial and interorbital regions, large orbits, short postorbital region, large otic notch, short presacral vertebral column, caudal chevrons, well developed limbs, and pentadactyl pes. All these features are equally characteristic of the three other well preserved specimens of *Amphibamus*, namely, Y.P.M. 794 (neotype), C.N.H.M. 2000 (type of *Miobatrachus*), and the specimen figures by Moodie (1916, plate 14, figs. 1, 2), now lost. They are sufficient to establish the identification of neotype with the type beyond reasonable doubt.

Figure 1 shows a revised reconstruction of the skull roof of Y.P.M. 794. Latex impressions from this specimen clearly show both postparietal and a horned tabular at the back of the skull table which Watson did not figure. Aside from these details the reconstructions agree in essentials. Additional preparation has developed scapulae and portions of the pelvis which are closely similar to those figured for "*Miobatrachus*," but

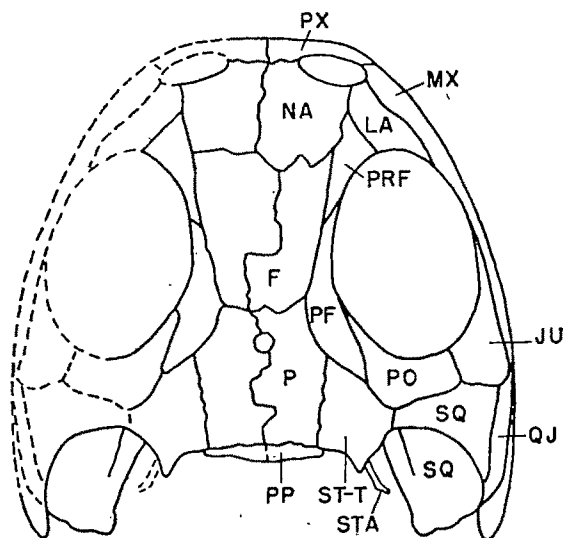


Fig. 1. *Amphibamus grandiceps* Cope. Reconstruction of skull roof of Y.P.M. No. 794, x 4. F frontal, JU jugal, LA lacrimal, MX maxillary, NA nasal, P parietal, PF postfrontal, PO postorbital, PP postparietal, PRF prefrontal, PX premaxillary, Q quadrate, QJ quadratojugal, STA stapes, ST-T supratemporal-tabular.

slightly more fully ossified. Apparently the ilium stood more vertically than in Watson's reconstruction and met the ischium in the acetabular region. A strong sacral rib runs from the 20th vertebra toward the ilium, directed somewhat backward. The limbs and scutellation also closely resemble "*Miobatrachus*." As the vertebrae are seen mainly from the dorsal surface in this specimen, the critical structure of the centra cannot be determined. The anterior ribs are slender, nearly straight, and slightly expanded distally; posteriorly they become shorter and very thin. Chevrons are present in the caudal region.

Moodie's plate 14, figs. 1 and 2, (1916), shows another well-preserved specimen which displays the large, broad head with large orbits, short temporal region, and prominent otic notch characteristic of *Amphibamus*. Measurements of this specimen, taken from the figure, are given in the third column of table 1. O. P. Hay described this in 1900, and gives its total length as 62 mm., slightly higher than I obtained from the figure, sug-

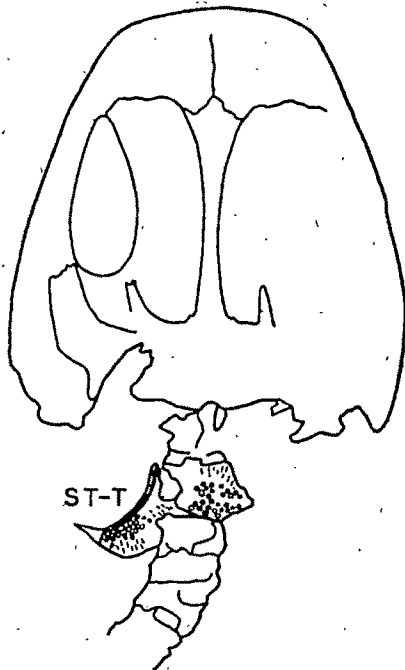


Fig. 2. *Amphibamus grandiceps* Cope. Portion of the type of *Miobatrachus romeri* Watson, C.N.H.M. 2000, showing displaced supratergital tabulars behind skull, $\times 4$. Lettering as in figure 1.

gesting that the reproduction may not be exactly natural size. However, the measurements clearly show that the proportions are closely similar to those of the type and neotype. Although the illustrations are inadequate to demonstrate the presence of tabular and postparietal, these elements were visible, for Hay (1900, p. 122) says, "Jugal, supratemporal, squamosal, and epiotic (= tabular) appear to be clearly distinguishable, the latter extending prominently backward."

Miobatrachus romeri:—Comparison of Watson's restoration of this specimen with his own drawing of Y.P.M. 794 shows close similarity in outline of skull, position and size of orbits and parietal foramen, and arrangement of roofing and palatal bones. The tabular region of the skull roof is concealed beneath impressions of palatal structures on both sides of the specimen; this possibly is the result of these bones having been broken from the skull prior to burial. Impressions of detached bones similar in outline to the tabulars of Y.P.M. 794 lie a few millimeters behind the skull, adjacent to the vertebral column (fig. 2). No mention of these elements is made by Watson. A transverse suture between parietal and postparietal may be seen, and the latter element is well developed. Identification of these elements in the "*Miobatrachus*" skull, and the close similarity of all other observable parts of skull and postcranial skeleton with corresponding structures in Y.P.M. No. 794 seems sufficient evidence to warrant reference of these specimens to the same species.

Mazonerpeton longicaudatum Moodie:—Re-examination of the type of this species has revealed so many discrepancies with Moodie's account that redescription seems desirable. Only the posterior roofing bones of the skull are preserved (fig. 3).

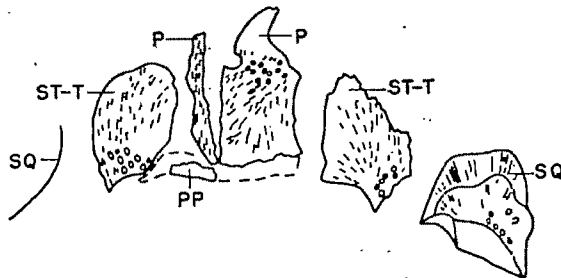


Fig. 3. *Amphibamus grandiceps* Cope. Skull roof of the type of *Mazonerpeton longicaudatum* Moodie, Y.P.M. No. 795, x 4, showing external surface as preserved in counterpart. Lettering as in figure 1.

Ornamentation of pits and ridges on the dorsal surface of the skull roof, preserved on the counterpart, indicates that the areas which Moodie described as orbits are in fact the impressions of the lower surfaces of the right squamosal and left tabular; the orbits actually lay anterior to the portion of the skull preserved in the nodule. Roofing bones are slightly separated from one another along the sutures, a feature which together with the small size of the animal suggests immaturity. Interparietals have only a small exposure on the skull table, and are imperfectly preserved. Elongate parietals (2.0 X 4.4 mm.) are united along a straight median suture and are pierced by a large (0.75 mm.) parietal foramen slightly forward of their center; the left parietal is broken longitudinally and both are incomplete anteriorly. Tabulars are large elements, possibly including the supratemporal although no trace of a suture could be found. They extend forward three-fourths the length of the parietals, (as far forward as the parietal foramen) and are nearly as wide as long. Their occipital margin curves back laterally to a short projecting horn. The large size of these elements and presence of a horn, suggests *Stegops*, in which the tabulars differ in the presence of posteromedial projections as well as a lateral horn, and in more pronounced radial arrangement of sculpture.

The squamosals are convex laterally and concave posteriorly adjacent to the otic notch. The posterior corner projects ventrally below the lower margin, covering the quadrate.

Close behind the right forefoot lies the displaced left lower jaw (fig. 4); its medial and lower surface is well preserved from the angle forward for the greater part of its length. This jaw is slender, especially anterior to the weak coronoid process. The articular cotylus projects inward, and a very short retroarticular process is present. Behind and below the articular expansion and inside the angular process is a large foramen. A suture between the angular and articular-prearticular runs just inside of the lower edge of the jaw from a point below the rear of the articular surface forward for several millimeters. There is a slight suggestion that the angular process is formed of surangular instead of angular, in the usual Amphibian fashion (see Romer, 1947, p. 61), and as Watson (1940, p. 202) has described in *Miobatrachus*. No indications of *Stegops*-like spines are visible on the ventral border of the angular.

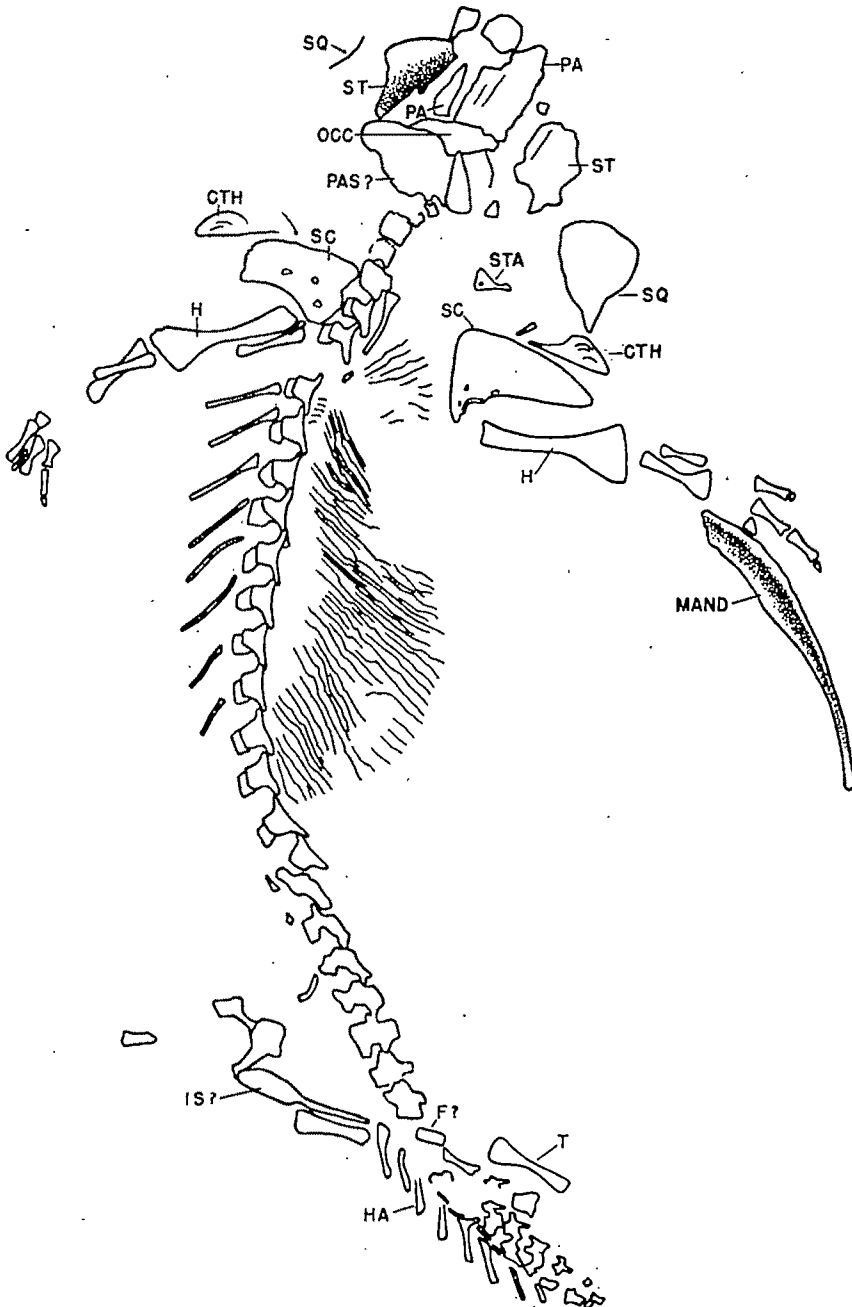


Fig. 4. *Amphibamus grandiceps* Cope. Type specimen of *Mazonerpeton longicaudatum* Moodle, Y.P.M. No. 798, x 3. CTH cleithrum, F femur, H humerus, HA haemal arches, IS ischium, MAND mandible, OCC occipital surface of skull, PA parietal, PAS parasphenoid, SC scapulecoracoid, ST supratemporal (possibly including tabular), STA stapes, SQ squamosal.

A well developed sloping occipital surface is sharply differentiated from the ornamented skull table; this region, unfortunately, is poorly preserved, and no details can be made out.

Moodie described the surface ornamentation of the skull roof as consisting of sharp tubercles and pits, which is essentially correct. In the peripheral portions of the bones there is a slight tendency for the pattern elements to be elongated, but as this is a small individual, growth characteristics of the sculpture are not pronounced. On the squamosal the sculpture radiates from the posterodorsal area. Around the anterior margin of the bone is an extensive band without pattern, indicating extensive overlap of the adjacent cheek bones along their sutures.

A displaced stapes lies behind the skull. It has a round footplate, relatively large stapedia foramen, and short straight shaft.

Moodie states that there are four or five cervical vertebrae. The anterior vertebrae are so poorly preserved that it is difficult to be sure of the number present, and no morphological detail by which they might be differentiated from those of the dorsal region is visible. He also states that "the number of dorsal vertebrae is identical with that of *Branchiosaurus* of Saxony" (1916, p. 61), which is reported to vary from 20 to at least 28, and he identified the 28th vertebra as sacral (p. 63). Twenty-two vertebrae lie anterior to the first bearing haemal chevrons; if one assumes that the sacral vertebra lay immediately in front of this, there were twenty-one presacrals.

Attempts to clean out the impressions of some of the dorsal vertebrae to learn their external form were not completely successful; the neural spines are low, and rather heavy transverse processes are directed downward along the sides of the pleurocentrum to articular facets for the ribs. Some indications of a separate intercentrum were seen. Watson's interpretation of the vertebrae of "*Miobatrachus*" would fit these limited observations satisfactorily. Caudal vertebrae (fig. 5) are exposed from the side and consist of three pieces: a neural arch, with almost no spine but long and dorsally extending zygapophyses; a short pleurocentrum, closely attached or fused to the neural arch; and an elongate but weakly ossified intercentrum. Haemal arches articulate beneath the anterior part of the intercentrum. Altogether the vertebral structure

is strongly suggestive of the Rhachitomi, which accords with Watson's observations on *Miobatrachus*.

The ribs are slender and two-headed.

Both scapulocoracoids are preserved, the right exposed from the lateral and the left from the medial aspects. This bone (fig. 5) is similar in form to that of other Paleozoic temnospondyls, with inwardly curving coracoid plate, screw-shaped glenoid, and supraglenoid, supracoracoid, and glenoid foramina distributed as in *Eryops*. The dimensions follow:

	mm.
Height scapula and coracoid	6.3
Height scapular blade above top glenoid	4.5
Length (anteroposterior)	4.4



Fig. 5. *Amphibamus grandiceps* Cope. A. Scapulocoracoid, and cleithrum of Y.P.M. 795 (type of *Maxonerpeton longicaudatum* Moodle), lateral view, $\times 8$. B. Two proximal caudal vertebrae of same specimen, about $\times 8$.

The right clavicle is preserved only in cross section and appears as a thin line running from the anterior point of the scapulo-coracoid inward toward the vertebral column; it cannot be determined whether or not it was expanded in typical labyrinthodont fashion. Both cleithra are preserved, lying near the anterior edges of the scapulae; they are expanded dorsally and bear faint concentric ornamentation which is suggestive of the growth lines on a clam shell. Ventrally they taper to a narrow point which lies close against the anterior edge of the scapula. Moodie identified a small bone lying directly beneath the vertebrae and parallel to the column as interclavicle. This bone is the size of a rib and the anterior expansion is not unlike the head of other ribs of *Mazonerpeton*; in view of the dissimilarity of this bone to the interclavicles of labyrinthodonts it seems more likely that it is a rib and that the dermal girdle is not completely preserved.

Humeri are somewhat as described by Moodie, slender bones with the expanded ends placed at right angles to one another. There is a conspicuously developed pectoral process. The ends of these bones are imperfectly ossified and no indication of either ect- or ent-epicondylar foramina are visible. Dimensions are given in table 1.

The radius is both shorter and more slender than the ulna; the latter bone is stout and about one-half the length of the humerus; on the right side a moderately developed olecranon process can be observed. The epipodials differ from those of *Amphibamus* in their unequal size, and from those of *Cephalerpeton* in their shortness, being about one-half the length of the humerus instead of over two-thirds the length of the latter. The total length of the front leg to the end of the first phalanx is 16 mm.

The carpus is unossified; remains of three digits are preserved on the right side, the bases of four metacarpals and the distal phalanges of one toe on the left. The last toe on the right side is covered by the end of the lower jaw. Moodie interpreted the fourth toe as the first. The phalangeal formula is 1 - ? -> 1-2.

Fragments of pelvis are visible on the right side but it has not been possible to elucidate their structure. Moodie (1916, p. 63) states that the left ilium is preserved: "It is elongate and cylindrical, its upper end adjoining the 28th vertebra."

Excavation along this element has uncovered a more extensive plate which meets a similar bone of the opposite side in V-shaped contact characteristic of the ventral elements of the primitive tetrapod pelvis; whether they are ischia or pubes cannot be ascertained from the parts exposed. *Amphibamus* (and "*Miobatrachus*") lack ossified pubes, but these elements might be present in a larger and more fully ossified form such as that under consideration. The anterior position of these elements in relation to the limb bones suggests pubes rather than ischia. No other pelvic elements have been identified.

The bone labeled femur in Moodie's figure 14a (1916) strongly resembles a tibia in its form, and a much larger bone exposed on the left (convex) side of the specimen passing beneath the vertebral column to appear again on the right is more probably the right femur.

The rear feet are not preserved.

Ventral scales are arranged in rows running outward and backward from the midline similarly to the pattern found in most "branchiosaurs" and other scaled Paleozoic amphibia; in a small anterior area the rows run forward and outward similar to those of "*Miobatrachus*." The scales were rounded, over-lapping, and marked with concentric striations, which give the appearance of "crescentic bundles of finer rods" mentioned by Moodie.

Comparisons: *Mazonerpeton* was described as a branchiosaur and has generally been accepted as such; Romer (1947, p. 119) suggested that it is a young rhachitome, which the present study confirms. The possibility that it might represent a larger individual of *Amphibamus*, suggested by the general form of the otic notch, shape of the posterior part of the lower jaw, number and observable features of the dorsal vertebrae, and the arrangement of the ventral scales, is confirmed by the detailed form of the posterior cranial elements, particularly the horned tabular—supratemporal. It differs from typical *Amphibamus* in having a coossified scapulocoracoid and relatively short radius compared to the ulna. Both of these characters are due to the greater maturity of this individual, indicated by its larger size.

Although this is the largest known specimen of *Amphibamus*, it still presents many characters of immaturity and may well be a larval form. We have no information at present as to the adult size and proportions of this animal.

Relationship to *Cephalerpeton* is excluded at once by the shorter vertebral column and especially by the temnospondylous nature of the vertebrae, by the presence of an otic notch and other skull features, by the coossified scapulocoracoid, relatively short forelimb, presence of only four toes in the manus, and differences in scutellation. It is obviously not a microsauro.

Relationship to the nectridian *Diceratosaurus* is excluded by the temnospondylous vertebrae, and also by the relatively small interparietals and form of the tabular horns.

Relationships: That *Amphibamus* is not a microsauro is evident from Watson's descriptions. The rhachitomous vertebrae, short vertebral column, and many other features contrast strongly with the lepospondyls. Watson (1940) demonstrated that the vertebral column of "*Miobatrachus*" resembled that of the Anura in the great development of the neural arch, presence of relatively small ventral blocks of the centrum, and reduced number of presacral vertebrae from that of primitive stegocephalians. He further pointed out resemblances to *Protobatrachus* in the structure of the palate, shoulder girdle, and pelvis. According to his interpretation of the skull roof there was also a trend toward the Anura in the loss of the tabulars and postparietals. On the basis of this analysis, Romer (1945a) erected a new order Eoanura for *Amphibamus* and "*Miobatrachus*."

The present interpretation of the skull roof of *Amphibamus* removes the most striking feature of Watson's comparison with *Protobatrachus* and the Anura.

It is possible that the preponderance of the neural arch in the vertebrae of *Amphibamus* foreshadows the anuran condition as Watson suggested, but it would be dangerous to trace the phylogeny of frogs solely on this structure which is so difficult to determine, and, in *Amphibamus*, not greatly different from other rhachitomes. The palate of *Amphibamus* is quite similar to that of the edopsoid rhachitomes except for larger interpterygoid vacuities and relatively broader posterior expansion of the parasphenoid. In the latter feature, particularly, it does approach *Protobatrachus* more closely than most other labyrinthodonts. Nevertheless, the resemblance is not surely the mark of relationship, for the proportions of the basal expansion of the parasphenoid are in part related to general skull proportions, and similarities may be found between *Proto-*

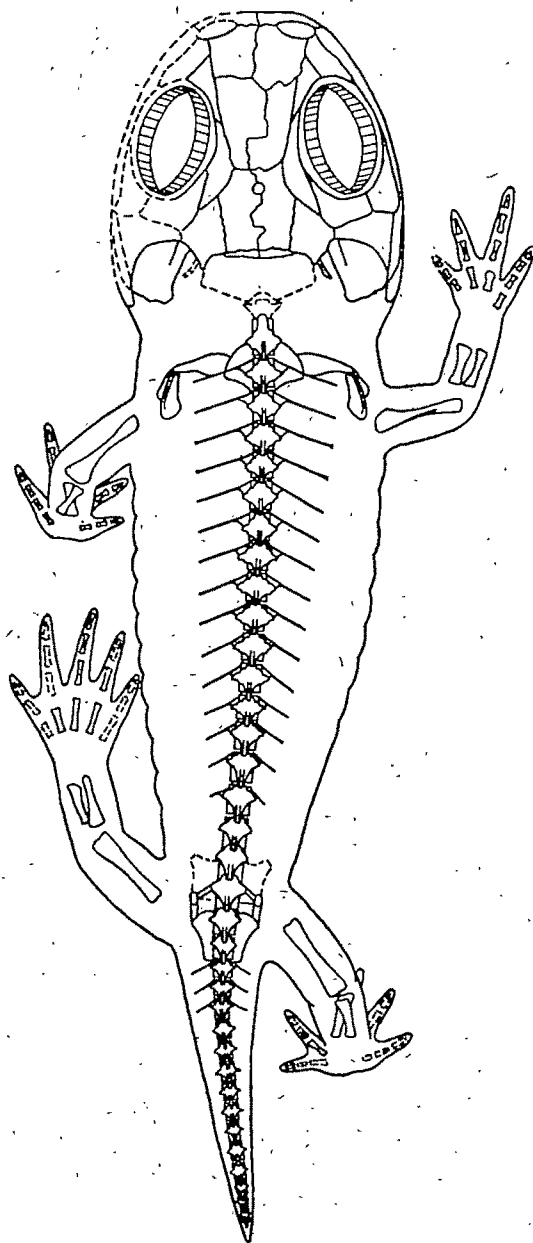


Fig. 6. *Amphibamus grandioeps* Cope. Restoration of skeleton x about $2\frac{1}{2}$. Modified from Watson (1940).

batrachus and other short-headed labyrinthodonts such as *Dvinasaurus* and *Stegops*. *Amphibamus* remains as plausible an ancestor as any for the Anura, but lacks positive features indicative of such relationship.

The typical rhachitomous labyrinthodont skull roof pattern of *Amphibamus* suggests that this genus may properly be included in the Labyrinthodontia regardless of its relationships to the Anura. Distinctive characters for family assignment are the relatively large and centrally placed orbits, the large supratemporal apparently united with tabular, large otic notch, and relatively short distance between otic notch and posterior border of the orbit.

The large pointed tabulars at once suggest the horned zatrachyids, among which the closest resemblance is to *Acanthostoma*. But *Amphibamus* lacks any trace of spines on quadratojugal and angular, and its tabular horns are simple and less developed than those of *Stegops*, the nearest zatrachyid both in age and geographic position. Moreover, the orbits are considerably larger relative to skull size than in *Stegops*, and much larger than in the later zatrachyid genera. There is no trace of an internasal fenestra (also absent in *Stegops*).

Posteriorly projecting tabulars and relatively large otic notches also characterize the Dissorophidae, particularly the Pennsylvanian genera *Platyrhinops* and *Mordax*; these genera have somewhat larger orbits than the zatrachyids. Further close resemblances to *Amphibamus* are found in the short postorbitals, broad frontals and nasals. Perhaps more important is the short vertebral column; in *Cacops* there are only 21 presacral vertebrae. There are differences in the palate, notably the relatively larger prevomers and correspondingly shorter interpterygoid vacuities in *Platyrhinops*, but these are not of such magnitude as to preclude family relationship (and the prevomers of "*Miobatrachus*" seem quite large). No trace of dorsal plates of dermal armor occurs in *Amphibamus*, but this specialization of Permian dissorhopids may not yet have developed in the Pennsylvanian. Altogether, the resemblances seem sufficient to justify reference of *Amphibamus* to the Dissorophidae.

Two other possible relatives of *Amphibamus* may be noted. Professor A. S. Romer has pointed out to me that the specimen of *Limnerpeton laticeps* Fritsch (1883, plate 36, fig. 1) from Tremosná belongs to the same group as *Amphibamus*. (The

type of that species appears to be the Nyrany specimen figured in plate 31, which Steen (1938, p. 261) has shown to be different.) Its vertebrae consist of *Amphibamus*-like neural arches and small ventral plates similar to those figured by Watson in "*Miobatrachus*." The lepospondylous vertebrae indicated in Fritsch's figure 91 do not appear to exist. Free haemal arches, which Miss Steen regarded as indicative of adelospondylous vertebrae, are known to be characteristic of the rhachitinous *Amphibamus*. The form of the scapula is quite like that of the genus under consideration; resemblances also may be found in the posterior end of the parasphenoid. Fritsch's figure suggests a large otic notch. Little can be seen of the skull structure in the electrotypes of the specimen. It may be noted that the scales (Fritsch, p. 149, fig. 90) have concentric striae like those of *Amphibamus* and in strong contrast to the radial pattern characteristic of microsaurs.

Another possible relative of *Amphibamus* is *Ricnodon limnophyes* Steen (1938, p. 227, figs. 13, 14.) This may be a differently crushed specimen of the Nyrany form described as *Mordex calliprepes* Steen (1938, p. 260, fig. 42) with which it agrees in (1) large tabular (+ supratemporal ?) bearing a small posterior horn; (2) presence of an interfrontal bone; (3) large, wide nasals; (4) moderate exposure of postparietals on skull roof; and (5) palate greatly studded with denticles.

Mordex has been referred tentatively to the trematopsids by Romer (1947, p. 167), but he figures it (*ibid.*, p. 158) in comparison with the dissorophids with which it agrees equally well except for the presence of a small interfrontal. *Ricnodon limnophyes* has a larger interfrontal, and as figured by Steen lacks the large otic notch. But its squamosal is a peculiar shape and may be distorted, eliminating the notch. These two forms agree with the dissorophids and zatrachyids in various respects but perhaps are closer to the former family. They lack the elongate external nares of the trematopsids and the internasal fenestra of these and the *Zatrachyids*.

In view of the close similarity in age, facies, and composition of the Mazon Creek and Linton faunas, it may well be asked whether any trace of *Amphibamus* occurs at the later locality. As pointed out above, *Platyrrhinops mordex* (Cope) appears to be a primitive dissorophid and resembles *Amphibamus* in many details of skull pattern. However, *Platyrrhinops* has considerably shorter interpterygoid vacuities and larger prevomers;

also its orbits are relatively smaller. Generic distinction between these forms seems reasonable on the basis of our present limited knowledge of them.

SUMMARY

Amphibamus grandiceps Cope is known from five specimens, the three referred by Moodie in 1916 and the types of *Mazonerpeton* and *Miobatrachus*. It is a typical rhachitomous labyrinthodont with enlarged, horned Supratemporal-tabulars and small postparietals, belonging to the family Dissorhophidae. Evidence from the largest specimen suggests that all known material is immature.

TABLE 1

Measurements in millimeters of	<i>A. grandiceps</i> type [from Cope's figure]	<i>A. grandiceps</i> Y.P.M. 794	Moodie, pl. 14, figs. 1-2	<i>Miobatrachus</i> romeri type CNHM 2000-	<i>Mazonerpeton longicaudatum</i> type, Y.P.M. 795
Length skull to rear margin table	16.8	13.7	15.5	12.8	—
Width skull	17.5	15.7	15.8	12.5	about 14
Post pineal length	5.8	3.7	4.5	4.2	3.5
Length orbit	7.0	6.4	6.6	about 6.6	—
Interorbital breadth	4.5	4.2	3.9	3.4	—
Ratio, skull length total length	.26	.21	.25	<.24	—
Ratio, width of skull length of skull	1.04	1.15	1.02	0.98	—
Length, tip snout to pelvis	50	55	about 40	43	48 from back skull
Total length	64	65+	—	>52 ¹	75± ^{2,4}
Length dorsal vertebral segment	—	1.9	—	1.6	2.1
Length humerus	5.4	4.7	—	4.4	6.0
Distal width humerus	—	2.1	—	1.5	—
Length radius	—	2.6	—	2.0	2.1
Length ulna	—	2.6	—	2.3	3.2
Ratio, length ulna length humerus	—	0.55	—	0.52	0.53
Length femur	7.5	6.5	—	5.9	7.0
Length tibia	4.2	3.8	—	3.2	4.0
Ratio, length tibia length femur	0.56	0.60	.67 ^{3,4}	0.54	—

1. Tail incomplete.

2. Estimated on basis of skull length 14 mm.

3. According to O. P. Hay.

4. Approximate.

Family incertae sedis

Microrepeton caudatum Moodie

Moodie, R. L., 1909, Jour. Geol. 17, 39-52, figs. 1-6; 1916, Carnegie Institute Washington Publ. 238, 52-57, plate 2, plate 5, fig. 4.

Eumicrorepeton parvum Moodie,

1910, Amer. Naturalist 44, 367-375, figs. 1-4;

1911, Proc. U. S. National Museum 40, 429-431, fig. 1;

1916, C. I. W. Publ. 238, 57-60, plate 3, figs. 1, 2; p. 65, fig. 15 b, c.

Type: Walker Collection (no. 12818), Chicago Natural History Museum no. UR 38, almost complete skeleton and impressions.

Type of Eumicrorepeton: Yale Peabody Museum no. 803, imperfect impression. Referred Y. P. M. 802 and U. S. N. M. no. 4400 (figured by Moodie), and U. S. N. M. nos. 4319, 4432.

The type skull of *Microrepeton* is broken off transversely just in front of the orbits (fig. 7), and shows no trace of the "minute nostrils" mentioned by Moodie. Sutures are indistinct; the median suture, those separating the circumorbital series from frontal and parietal, a doubtful transverse suture between frontals and parietals, and on the left side a possible suture around the postorbital are all that could be determined. In a few places where the bone has broken away from the matrix the impression of minute ornament pits can be observed. Several significant features of the external skull structure may be determined.

Most important of these is the well-developed otic notch, best seen on the left side of the counterpart specimen. It is deep and slopes back strongly exactly like that of *Amphibamus*. There is

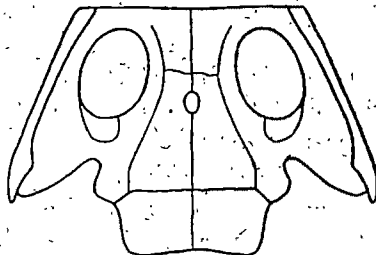


Fig. 7. *Microrepeton caudatum* Moodie. Skull of type, C.N.H.M. UR 38, x 5.

a long, sloping occiput, now crushed into the plane of the skull roof. The orbits are of moderate size, oval, directed outward as much as upward, separated from the frontal by the prefrontal and postfrontal bones. A few tiny wedge-shaped bones in the left orbit may be fragments of the sclerotic plates. Between the posterior halves of the orbits lies the large parietal foramen. Impressions of the cheek bones are not sufficiently continuous to reveal its structure, nor is aught but the outline of the lower jaw visible.

A suggestion of an impression of the expanded posterior end of the parasphenoid, bearing minute teeth, is seen on the counterpart specimen.

Moodie's reconstruction (1909, fig. 5) is inaccurate and suggests far more than can be observed.

Twenty vertebrae lie between the skull and the point where the femur crosses the vertebral column; although the sacral vertebra could not be identified with certainty, a presacral vertebral count of 19 or 20 is probable. Cervical vertebrae have short stout transverse processes. Impressions of the vertebrae are incomplete, but in the posterior dorsal region impressions reveal low neural spines, strong zygapophyses, and extensive neural arches reaching low on the sides of the vertebrae. The structure is like that described by Watson in *Miobatrachus* except that the ventral elements could not be distinguished. Direct comparison of the specimen with the type of *Miobatrachus romeri* confirms the resemblance. The proximal caudal vertebrae consist of large neural arches and well developed intercentra bearing elongate haemal arches. These are separated by a space which presumably contained the notochord.

Two slender curved ribs are preserved.

Limb bones are poorly preserved; Moodie has indicated their general positions. I cannot agree with his identification of the elements of the shoulder girdle, which are exceedingly indistinct and unidentifiable. There is no trace of the pelvis.

The ventral armature consists of a series of overlapping rows of small lenticular scales which diverge posteriorly from a median row of larger scutes; the impression is not so clear as that in the *Miobatrachus* specimen but is exceedingly similar to it.

The lateral line of the tail and color bands which Moodie

described (1909, pp. 47-49, figs. 4-6) can no longer be observed. Certain features of the specimen suggest that the "color bands" may have been impressions on the rock due to internal structures rather than rows of pigmented scales. Round, slightly overlapping scales can be seen on the tail, especially on the counterpart.

Discussion of the relationships of *Micrerpeton* is best deferred until after certain additional specimens have been mentioned.

Eumicrerpeton parvum Moodie:—Both of the Yale specimens (Y.P.M. no. 802 and 803) are impressions of the lower surfaces of larvae which show little besides body outline and the cast of the intestine. The skulls are slightly broader than long, have large orbits well separated by a broad skull roof, and appear to have had otic notches. On the larger specimen, no. 803 (fig. 8), there is a suggestion of a triangular area of parasphenoid teeth at the back of the palate, and a slender parasphenoid bar between large interpterygoid vacuities.

Clavicles and interclavicles cannot be separated; together they form a transverse girdle a short distance behind the skull, the outer ends of the clavicles curving backward. Nothing can be seen of the primary shoulder girdle, which may have been entirely cartilaginous in such young stages. Short portions of

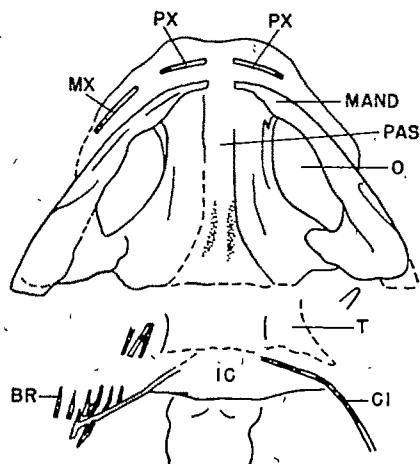


Fig. 8. *Micrerpeton caudatum* Moodie. Skull of type of *Eumicrerpeton parvum* Moodie, Y.P.M. No. 803, x 6. BR possible branchial filaments. CL clavicle, IC interclavicle, O orbit, MAND lower jaw, PAS parasphenoid, PX premaxillary, T skull table.

the humeral shafts were ossified, and in no. 802 there is a suggestion of one bone in the left forearm. No trace of the pelvis is to be seen in that specimen, and only a poor indication of the left thigh. In no. 803, a portion of the shaft of the femur may be seen.

Far better preserved is U. S. N. M. no. 4400 (fig. 9), which shows clear skeletal impressions in addition to the cast of the digestive tract which largely occupied Moodie's attention. The large supratemporal-tabular with a small posterior horn is definitely visible on both sides of the skull table. Behind the sharp boundary of the skull table are impressions of the sloping occipital surface, but the rear outline of occiput and condyles are obscure as in all these specimens. Postparietals cannot be distinguished. The interorbital and nasal regions are broad; the large parietal foramen lies between the rear half of the orbits. Tuberculation on the skull roof is indicated, but the squamosals appear smooth at this stage.

No useful data concerning postcranial skeleton can be obtained; the general appearance has been described by Moodie.

These three specimens, and the two to be mentioned below, appear to be somewhat differently preserved individuals of *Micrerpeton caudatum*. The short, broad skulls, anteriorly placed pineal foramen, and large orbits close in front of the otic notch indicate relationship to that form. Details of skull pattern in U. S. N. M. no. 4400 agree with and supplement those of the type. Similarities in proportions are evident from measurements given in table 2.

U. S. N. M. no. 4319—Undescribed branchiosaur.—This is the smallest individual branchiosaur so far recovered from Mazon Creek, its total length being about 23 mm. In spite of small size, considerable details of skull structure are preserved, and neural arches of the vertebrae are well developed. The fracture of the nodule does not include the levels of the limb bones, although traces of the left forelimb outline may be seen. The skull is short, broad, with large and widely separated orbits and a large parietal foramen lying between the middle of the orbits. The skull table projects well behind the quadrate articulation, and is drawn out laterally into tiny tabular horns.

Sutures between nearly all the roofing elements can be distinguished, only the quadratojugals, maxilla and premaxillae being obscure or missing. The anterior portion of the skull

roof is missing, but the entire outline may be seen on the lower impression.

The supraoccipital is broad, slightly rounded at its dorso-lateral angles, and faintly grooved near the midline.

Interpterygoid vacuities are extremely wide. The parasphenoid rostrum is fairly wide, of uniform width, similar to that in such stereospondyls as *Metoposaurus*. There are no traces of teeth along the anterior process, but a triangular patch lies just at its base where the bone expands to floor the braincase, as in *Amphibamus*.

About 22 vertebrae are preserved, and there are indications that the last are in the pelvic region. Thus the column is similar in length to *Amphibamus*.

Identification of this small animal is difficult. Its resemblances to *Micrerpeton* and "*Eumicrerpeton*" are sufficient to justify references to the same species of *Branchiosaur*. Observable details of the skull roof pattern agree well with *Amphibamus*, but the form is so small and the characters shown are so generalized "stegocephalian" that it would be difficult to assert that it could not be the larva of some other labyrinthodont.

U. S. N. M. no. 4482.—This small and imperfect specimen shows but few traces of the skull. The double-headed ribs are well preserved and show, on the more anterior ones, a slight distal expansion. About sixteen vertebrae and one forelimb are preserved. Measurements are given in the table.

Relationships: *Micrerpeton* resembles *Amphibamus* in the following respects:

1. Well-developed otic notch
2. Sloping occiput
3. Large orbits
4. Type of ornamentation
5. 19 or 20 presacral vertebrae
6. Known structure of vertebrae
7. Ribs
8. Details of ventral scutellation
9. General size of limb bones
10. Haemal arches

Observable differences between *Micrerpeton* and *Amphibamus* include:

1. Skull length $1/8$ to $1/5$ total length, compared to about $1/4$ total length in *Amphibamus*.
2. Skull width appreciably greater than skull length instead of about the same.
3. Tail longer.
4. Pineal foramen between orbits instead of behind them.
5. Possibly less developed horn on tabular (or supratemporal).

Evaluation of these differences is difficult. The animals do not look alike, yet most of the tangible distinctions are characters which are known to vary during growth. All specimens of *Amphibamus* lack the distal portion of the tail so that ratios of head to total length appear greater than their true value. Quite possibly complete specimens would give substantially longer lengths and bring these ratios for the two groups within reasonable limits of variability. Skulls of *Micrerpeton* and "*Eumicrerpeton*" are all crushed flat and considerably widened posteriorly. It is not possible to accurately reconstruct these, but if the depth was at all comparable with that of *Amphibamus* the width could not have greatly exceeded the length. This distinction, then, is uncertain.

Possibly more significance is to be attached to the more anterior position of the pineal foramen, but even this may change with growth.

A possibly valid distinction between *Micrerpeton* and *Amphibamus* may lie in the trend to increase of width/length ratio of the skulls with increase in size in the former genus. Such a trend would not lead to the equidimensional amphibamid skull. But this trend itself may be an artifact due to crushing.

Regression of skull length against total length is not conclusive as to trend and could well be interpreted either on the basis of growth or of different proportions. *Micrerpeton* specimens are less than 40 mm. in length compared to 50-75 mm. length in *Amphibamus*, a sufficient difference to account for substantial changes of proportions.

Finally, the most characteristic feature of the *Amphibamus* skulls is the form of the supratemporal; in *Micrerpeton* this is not determinable except in U.S.N.M. 4400, which does resemble *Amphibamus* in this feature.

The temptation is strong to throw these forms into the synonymy of *Amphibamus* and attribute the differences to dif-

ferential growth. But it seems impossible at present to prove such synonymy and better advised to retain *Microperpeton* as a separate genus of "branchiosaur."

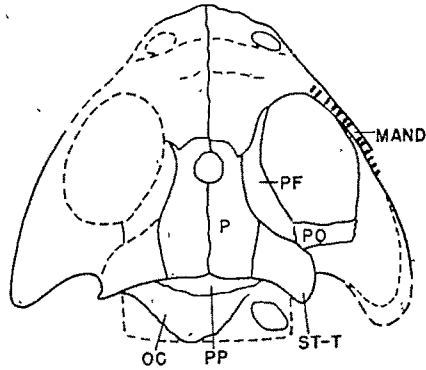
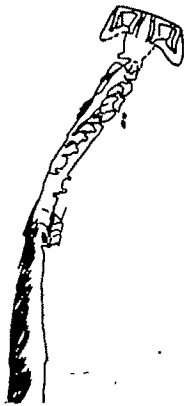


Fig. 9

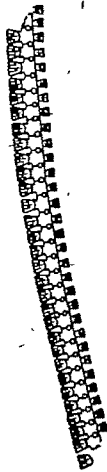


Fig. 10

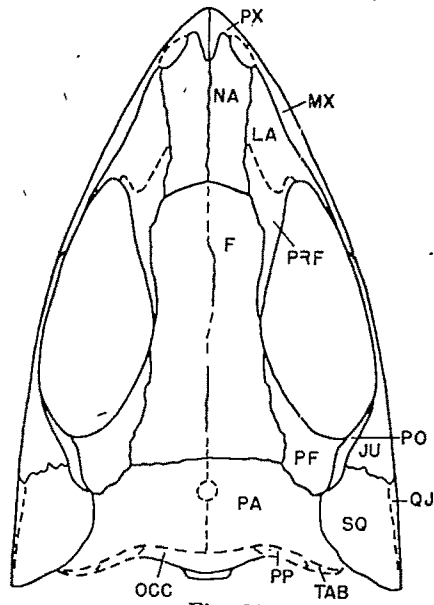


Fig. 11

Fig. 9. *Microperpeton caudatum* Moodie. Skull of U.S.N.M. No. 4400, x 6. Lettering as in figures 1 and 4.

Fig. 10. *Sauroplesura* sp. U.S.N.M. No. 18125, x 2.

Fig. 11. *Cephalerpeton ventriarmatum* Moodie, Y.P.M. No. 796. Skull roof, reconstructed, x $2\frac{1}{2}$. F frontal, JU jugal, LA lacrimal, MX maxillary, NA nasal, OCC supraoccipital, PA parietal, PF postfrontal, PO postorbital, PRF prefrontal, PP postparietal, PX premaxillary, QJ quadratojugal, SQ squamosal, TAB tabular (or supratemporal).

Equal difficulties beset attempts to allocate these animals to family position within the Rhachitomi. No genera are known to me with the combination of large orbits, short faces, and such anteriorly placed pineal foramina. Some specimens of *Branchiosaurus*, as that figured by Bulman and Whittard (1926, p. 539, fig. 1), and the highly aberrant Triassic Brachyopids, are all that approach it, and the latter are obviously not related. The branchiosaur resemblance is chiefly in features of immaturity. The series of *Actinodon* skulls figured by Romer shows posterior migration of pineal foramen relative to orbits with growth, and it is possible that larger specimens of *Micrerpeton* would have longer skulls and pineal foramen behind the orbits. Such changes could bring it very close to *Amphibamus*, but other changes in proportion could give rise to quite different forms.

Consequently family assignment of *Micrerpeton* is not possible at present. It may represent young of *Amphibamus*, but this cannot be demonstrated. Here it is listed separately as a Rhachitome incertae sedis.

Indeterminate labyrinthodont

Erierpeton branchialis Moodie 1912

Moodie, 1912, K. U. Sci. Bull., vol. 6, no. 2, pp. 328-330, plate 1, fig. 8, plate 2, fig. 1.

1916, C.I.W. Publ. 288, pp. 65, 69-70, plate 8, fig. 4, text fig. 15a.

Type: Impression of skull and soft body parts in nodule, Yale Peabody Museum no. 801.

The skull impressions are susceptible to alternate interpretation from that of Moodie, who regarded them as mandible, basibranchial, and paired hypohyals. The paired impressions are strongly suggestive of pterygoids, and the median one of the anterior portion of the parasphenoid of a palate with large interpterygoid vacuities. The mandible is massive for an animal of this size, rather than slender as described by Moodie (1916, p. 70); nor is there any evidence in the impression to support his statement that the symphysis was not a complete sutural union. Most striking is the posterior prolongation of the mandible to an extent which suggests that the quadrate lay well behind the pterygoid vacuities in contrast to *Amphibamus*. Olson regarded *Erierpeton* as indeterminate, and

TABLE 2

Measurements in millimeters of	<i>Microperpeton</i> <i>caudatum</i> type C.N.H.M. 12318	<i>Eumicroperpeton</i> <i>parvum</i> type Y.P.M. 803	<i>E. parvum</i> Y.P.M. 802	<i>E. parvum</i> U.S.N.M. 4400	U.S.N.M. 4319	U.S.N.M. 4432
Length skull to rear margin table	—	8 ²	4.4	6.3	4.6	—
Width skull	8.6 ¹	7.0	6.0	9.7	6.0	7
Post pineal length	2.1	—	—	2.3	—	—
Length orbit	2.7	—	—	2.8	1.9	—
Interorbital breadth	2.0	1.9	—	2.3	1.7	—
Ratio, skull length total length	—	.13	.16	.17	.19	—
Ratio, width of skull length of skull	—	1.4	1.36	1.54	1.30	—
Length, tip snout to pelvis	27 ²	23	20	29	—	—
Total length	49	39	28	38	24 ²	—
Length dorsal vertebral segment	0.9	—	—	—	—	1.2
Length humerus	3.7	1.6	—	2.5	—	3.5
Length radius	—	—	—	—	—	2.1
Length ulna	—	—	—	—	—	1.7
Length femur	3.0+	—	—	3.9	—	—

1. Probably too large, as result of crushing

2. Approximate

suggested dropping it from the faunal list. Romer (1947, p. 119) suggested that it may be a larval rhachitome of the *Eugyrinus-Pelion* type. Conceivably it might be an immature *Cephalerpeton*, but there is no positive evidence of this. What little evidence exists supports Romer's conclusion, and the name may be retained to indicate its presence, although it would be impossible ever certainly to identify another specimen with it.

Order Embolomeri Cope

Family Eogyrinidae Watson ?

Spondylterpeton spinatum Moodie 1912

Moodie, 1912, Kansas Univ. Sci. Bull., vol 6, no. 2, pp. 355-357, plate 8, figs. 1, 2; plate 9, fig. 1.

1916, C.I.W. Publ. 238, p. 179, fig. 39, plate 4, figs. 1, 2.

Romer, 1930, A.M.N.H. Bull. 59, pp. 132-133, fig. 25.

Type: Yale Peabody Museum, no. 793. Nodule containing 5 caudal vertebrae.

The pleurocentra are suturally united to both neural and haemal arches; intercentra are equal in size to pleurocentra, without apophyses. A large form not identifiable with better-known genera.

Subclass Lepospondyli

Order Nectridia

Family Urocordylidae

Sauropleura sp.

U.S.N.M. Div. Vertebrate Paleontology, no. 18125. Half nodule with incomplete impression.

A specimen in the Lacoe collection which Dr. David H. Dunkle kindly brought to my attention reveals the presence of the Nectridian genus *Sauropleura* in the Mazon Creek fauna (fig. 10). Both the anterior part of the skull and distal end of the tail are missing, and little structure can be determined beyond the highly characteristic vertebrae and gastralia. Apparently the specimen is a young individual; the preserved length of the vertebral column from the back of the skull is only 61 mm.; more than half of this is tail. The posterior width of the skull is $5\frac{1}{2}$ mm.

The spines of the caudal vertebrae expand in characteristic Urocordylid fashion, their distal ends broad and nearly touching as in *Sauropleura* rather than slender and elongate as in *Urocordylus* or *Ctenerpeton*. Both neural and haemal spines bear radiating ridges which extend into minute denticulations at the ends of the spines; six ridges and serrations are present on the neural spines; the haemal spines, although slightly broader, have only four.

Closest resemblances to this animal are found in the Linton, Ohio, species, *Sauropleura pectinatus* Cope, which differs in the presence of a larger number of ridges on the expanded

spines (up to 11 according to Cope, 1868, p. 216; 1875, 378). Possibly the Mazon Creek form belonged to a distinct species, but the present specimen is too imperfect to demonstrate this.

Order Aistopoda

Family Dolichosomidae

Phlegethontia mazonensis Gregory

Gregory, J. T., 1948, *Am. Jour. Sci.* 246, pp. 636-663, figs. 1-6, plate 1.

Type: U.S.N.M. Div. Vertebrate Paleontology, no. 17097, nodule in counterpart with complete skeleton.

A second specimen in the U.S.N.M., no. 4313, consists of a series of 19 dorsal vertebrae and assorted ribs of a much larger individual than the type. Individual vertebrae are 3.3 mm. long from tips of the zygapophyses, and have centra 2.6 mm. long. Their height is about 3.5 mm., and width across the transverse processes 3.2 mm. Neural canals are large cylindrical, completely surrounded by bone as figured previously. A slight intervertebral space between centra is indicated.

The assignment of the Aistopoda to the Reptilia, suggested in the article cited above, has been questioned by Professor A. S. Romer on the grounds, first, that the reduction of the skull roof in this genus is an amphibian feature not shared by primitive Reptilia; second, that the unusually complete ossification of the braincase is more like primitive amphibians such as *Edops* (Romer and Witter, 1942) than early reptiles such as *Captorhinus* (Price, 1935); third, that such high specialization is unlikely in the Reptilia at the time of their first appearance whereas the late Pennsylvanian Amphibia had already undergone a long period of evolution and diversification; and finally that the character of several cervical vertebrae is not pertinent to distinguishing between these classes of vertebrates.

Inasmuch as the fenestration of the temporal region has occurred in both Amphibia and Reptilia, this character cannot be regarded as critical. The boundaries of the fenestra in *Phlegethontia* are more like those of some reptiles than any amphibian. And other reptiles (Pelycosaur) with fenestrated skulls are known from somewhat later Pennsylvanian deposits (Romer and Price, 1940, pp. 33-34):

Although Romer (1949, p. 158) has stated that there were about seven cervical vertebrae in primitive tetrapods, an in-

spection of figures of several labyrinthodont skeletons fails to show any with more than two specialized cervicals. Elongation of the neck with resulting modification of the cervical vertebrae is characteristic of the amniotes. Even primitive reptiles have relatively short cervical regions, so that the eight modified anterior vertebrae of *Phlegethontia* are probably unique among Pennsylvanian tetrapods. They were interpreted as indicative of a long-necked (and thus probably amniote) ancestor, but reconsideration of the evidence suggests that this is more probably another independent specialization of the aistopods; no such possible ancestor is known in the Paleozoic, unless it be *Cephalerpeton*, which had a moderately extensive cervical region.

The structure of the braincase is the critical character in estimating the affinities of this Order. As was pointed out previously (Gregory, 1948b, p. 653) there is marked resemblance to snakes and to various burrowing animals in the skull of *Phlegethontia* which must be attributed to adaptive modification. However, this skull type could be easily derived from the more platybasic neurocranium of such a primitive labyrinthodont as *Edops* by constriction of the interorbital region and expansion of the otic capsule. Aside from the lack of ossification in the orbitotemporal region, the braincase of *Captorhinus* would serve equally well as a point of departure from which to derive the aistopod skull; but an accessory hypothesis of secondary ossification is then required. Consequently reference to the Amphibia is simpler, although not conclusively demonstrated.

CLASS REPTILIA

Order Captorhina

Family Protothyrididae

Cephalerpeton ventriarmatum Moodie

Moodie, R. L., 1912, Kansas Univ. Sci. Bull., vol. 6, no. 2, pp. 850-852, plate 1, fig. 4; plate 7, fig. 12. 1916, Carnegie.

Institute of Wash. Publ. 288, pp. 133-134, fig. 29.

Gregory, J. T., 1948a, Am. Jour. Sci. 246, pp. 550-552, figs. 1-2.

Type: Peabody Mus. Nat. Hist., no. 796, mold of crushed and partly disarticulated skull, the first 26 vertebrae and ribs, both forelimbs, and ventral armor.

A revised restoration of the skull is shown in figure 11; it differs from my earlier attempt in the greater interorbital width and interpretation of the postorbital portion of the skull roof. The impression previously regarded as parietal is more probably a portion of the displaced supraoccipital.

Evidence that *Cephalerpeton* was closely related to the captorhinomorph reptiles led me to revive Baur's suggestion that the microsaurians were reptiles (1948a, p. 565). Professor Romer has orally disputed this view, maintaining that the microsaurians are holospondylous amphibians with a large intertemporal bone at the back of the skull, quite unlike the captorhinids. We agree that this group has nothing to do with reptilian ancestry. Although *Hylonomus* and related primitive reptiles on which the term Microsauria was founded must be excluded from the group, it will be more conducive to stability of nomenclature to continue using Microsauria in the sense of Romer (1945) than restricting it as I suggested in 1948.

Unfortunately the critical posterior portion of the skull table is missing from *Cephalerpeton*. The preserved portion agrees in pattern with *Captorhinus*, and also with some of the aberrant microsaurians (in the sense of Romer, 1945, pp. 159-160). The postcranial skeleton is distinctively reptilian in its pentadactyl manus, separate coracoid ossification, and rod-like gastralia, so that it may confidently be associated with the Captorhina. Its upper dentition closely resembles that of *Romeria texana* Price (1937, p. 97, plate 6, fig. 1) from the Wichita Group of Texas, with which the anterior portion of the skull roof agrees fairly well. Reptilian skeletons of similar size and character are known from the slightly later Pennsylvanian deposit at Linton, Ohio, as *Eusauropleura digitata* (Cope)³ and *Tuditatus punctulatus* Cope; until skulls of these animals are discovered the degree of their relationship to *Cephalerpeton* will remain unknown.

In spite of the priority of Hylonomidae over Protothyrididae as a family name for these unspecialized small captorhinomorphs, the unsatisfactory preservation of *Hylonomus* makes it undesirable as a family type. Romer (1945, p. 592) refers (with query) *Tuditatus* and *Eusauropleura* to the *Solenodonsauridae*, a family based upon an equally poorly known genus

³ Romer (1950) suggests that this skeleton may possibly belong to one of the microsaurians.

of somewhat larger size. Until more is known of these reptiles, there is no good reason not to refer all the American forms to the Protothyrididae.

The Protothyrididae, like the Limnoscelidae, are extremely primitive captorhine reptiles with predaceous dentition. Their small size makes them even more ideal ancestors for later reptiles than *Limnoscelis*. The origin of these families from embolomorous labyrinthodonts is obscure; absence of an otic notch makes Seymouriamorph derivation unlikely.

Indeterminable specimens

Mazonerpeton costatum Moodie

Moodie, R. L., 1912, Kansas Univ. Sci. Bull., vol. 6, pp. 341-343, plate 2, fig. 3, plate 8, fig. 4, plate 9, fig. 2;
1916, C.I.W. Publ. 238, pp. 63-65, fig. 14b.

Type: Yale Peabody Museum no. 800; nodule in counterpart with portions of skull and skeleton.

The tetrapod nature of this imperfect specimen is questionable. A confused mass of impressions of the inner surfaces of skull bones lies at the end of the vertebral column. Portions of the condyle and margins of the foramen magnum can be distinguished. Somewhat detached from the remainder of the skull is a maxillary (labeled clavicle at the lower left of Moodie's figure) studded with numerous, closely spaced, short, conical teeth of equal size throughout.

Near the center of the nodule is a long, triangular, symmetrical element, forked at its broad end, and bearing dermal bone sculpture on the convex side. Moodie labeled this clavicle, which it cannot be; no tetrapod possesses such an element. Possibly it is a median gular of a fish.

Two "ribs" which meet by the broad, bifurcated end of the above mentioned bone differ from the heavier ribs preserved elsewhere and appear to form a symmetrical pair. Possibly they are hyoid or branchiostegal elements.

A series of thick ribs lies detached from the vertebral column. They are holocephalous, with slightly expanded distal ends. Little can be determined of the vertebral structure. There is no trace of limb bones.

The specimen presents sufficient information to show that it does not belong to any of the better preserved Mazon Creek tetrapods, but not enough to indicate its true affinities.

Moodie (1916, p. 65, fig. 15e) figured a "rib of *Mazonerpeton costatum*," Yale Peabody Museum no. 804. This cannot be identified with the type of that species. It is an indeterminate shaft lacking terminations.

Erpetobrachium mazonensis Moodie

Moodie, R. L., 1912, Kansas Univ. Sci. Bull. 6, 353-354, plate 2, fig. 2, plate 8, fig. 8;
1916, C.I.W. Publ. 238, p. 150, p. 65, fig. 15D, plate 3, fig. 8.

Type: Yale Peabody Museum no. 799. Nodule in counterpart with limb bones.

Bones of at least three limbs are present in this specimen, along with plant impressions. Preservation is too imperfect to permit determination of the bones present, or of the kind of tetrapod represented. They are fairly slender for an amphibian and larger than those of any of the better-known Mazon Creek forms, being 23 to 24 mm. long each.

Possibly to be associated with this, solely on the basis of size, is a limb bone, probably femur, preserved as impression in counterpart in U.S.N.M. no. 4377. Its length is 18.7 mm., its width at the proximal end 5.0 mm. The ends of the bone appear to have had cartilaginous extensions.

These remains are entirely indeterminate, even the class of vertebrates represented being in doubt. *Erpetobrachium* is a *nomen vanum*.

Non-vertebrate material previously described as Amphibian.
Amphibamus thoracatus Moodie

Moodie, 1911, U.S.N.M. Proc. 40, 431-433, fig. 2.
1916, C.I.W. Publ. 238, 131-132, fig. 14.

Type: U.S.N.M. Div. Vert. Pal. no. 4306, nodule in counterpart.

Moodie thought he detected a triangular skull, large interclavicle, and bones of the forelimb in this nodule, but close scrutiny fails to reveal aught but plant remains. The "interclavicle" shows parallel leaf venation, and some of the other impressions also may be plant. The supposed skull impression is such that the right lower jaw would have to be present in both halves of the nodule in different places. The "species" may safely be forgotten and dropped from further consideration of the Pennsylvanian fauna.

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MARINE CREVASSE FILLINGS IN THE LOTBINIERE REGION, QUEBEC

F. FITZ OSBORNE

ABSTRACT. Peculiar ridges in an extensive region on the south shore of the St. Lawrence River near Quebec, are the result of the filling of crevasses in drift-burdened and stagnant ice by sands and gravels of a late Pleistocene sea. The presence of such easily eroded features below the marine limit indicates that the ice must have persisted until the sea level had fallen to a low, but as yet undetermined elevation. Topographic maps have features which suggest that a considerable part of the valley on the south side of the St. Lawrence was protected by stagnant ice.

INTRODUCTION

QUEBEC CITY is strategically situated on the route to the interior of North America. The high ridges of the Appalachian region here come against the Laurentian upland to form the eastern vertex of the St. Lawrence lowlands. The entrance to the lowlands is thus through the narrow gap in which the St. Lawrence River now flows and through which sea water invaded the lowlands in late Pleistocene time. The deposits formed during that time are, therefore, of particular interest in working out the history of the region. Considerable work has been done to determine the upper limit of marine submergence (Goldthwait, 1911, 1914), but the Pleistocene deposits of the lowlands at lower elevations have not received much attention.

In driving from Quebec to Montreal by the road on the south side of the river, a geologist cannot help contrasting the topography with that along the highway on the north side of the St. Lawrence. On the north side, terraces with pronounced cusps are prominent, whereas, on the south, such terraces are absent. Furthermore, on the south side, ridges of sand and gravel, which superficially resemble eskers, stand above sand plains at elevations below the upper limit of the late Pleistocene sea. Examination of the ridges shows that they were originally fillings of channels in a stagnant ice sheet that protected the unconsolidated deposits of the surface from watermarking by the shallowing sea.

LOCATION OF CREVASSE FILLINGS

The ridges occur sporadically in a region of about 450 square miles in Lotbinière, Nicolet, Mégantic, and Arthabaska

counties, in the area covered by the Lyster, Bécancour, and Portneuf (one mile) sheets of the National Topographic series of the Department of Mines and Resources, Ottawa. Figure 1 shows the outline of the area together with a key to the topographic sheets, which are listed under maps in the "references." The Canadian National Railways, Intercolonial Branch, crosses the region, which in the main is but sparsely settled. Up until recently, a few secondary roads provided access to the area, but the Laurier highway (No. 3) now links Montreal and Quebec *via* the south shore of the St. Lawrence and makes the region easily accessible by motor car.

The borrow pits and road-cuts along the highway expose sections of the sand and gravel deposits. Much of the area is covered by a scrubby second growth of mixed hardwoods and softwoods, so that the smaller topographic features are easily overlooked. However, late in 1949, forest fires swept much of the region, and many of the minor topographic forms are temporarily easily observed.

GEOLOGICAL SETTING

The outcrop of the St. Lawrence and Champlain fault, which forms the boundary between the lowlands of the St. Lawrence and the Appalachian region, crosses the area in a N 55° E

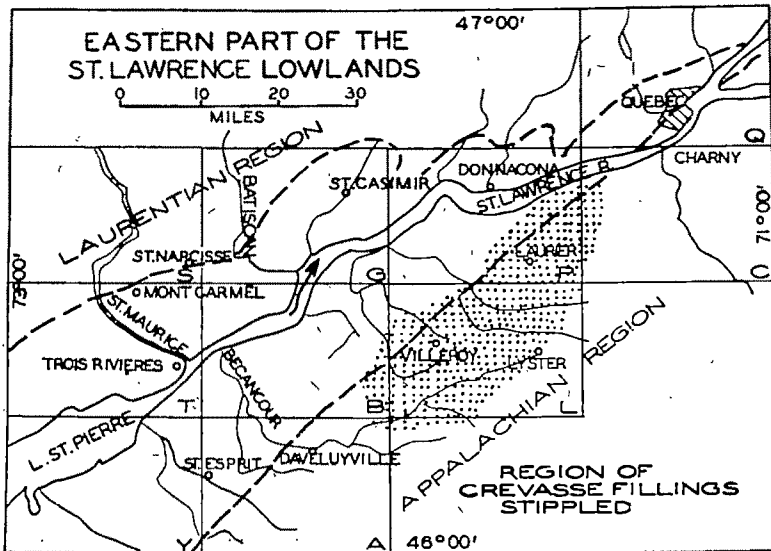


Fig. 1. Location map. The broken lines show the limits of the lowlands.

direction. The overburden is so continuous, particularly in the area covered by the Lyster sheet, that the precise position of the fault cannot be determined by ordinary mapping. The broken and higher ground that might be expected to mark the Appalachian front occurs about ten miles southeast of the boundary fault.

The region is a sand plain whose uniformity is broken only by stream valleys, by some sand dunes, and by the features described in this paper. The surface slopes southwestward at about four feet a mile from the 450-foot to the 350-foot contour; there is, however, on the northwestern side a tendency for the slope to be more toward the nearby channel of the St. Lawrence.

The plain is characterized by well-bedded medium- to coarse-grained sand. The abundance of sub-angular boulders from a Laurentian source in the sand is noteworthy. In some cultivated fields, boulder heaps are as large as those commonly seen in morainic regions. Locally small deposits of alternating beds of fine sand and silt may be seen, and some peat (Ells, 1889) occurs. Till was not observed at the surface, although it was seen where a stream channel had been deepened for an irrigation project. Here blue boulder clay underlies the sand 15 feet below the general surface of the plain.

DESCRIPTION OF CREVASSE FILLINGS

Tracings of parts of the topographic maps of the region are shown in figures 2, 3 and 4 in which the form and relationships of some of the higher ridges are shown. As will be seen from the maps, the ridges have narrow bases and they rise steeply to as much as 75 feet above the surrounding sand plain. Offsets such as those on the ridge $1\frac{3}{4}$ miles southeast of Villeroy (fig. 2) are common. Despite the continuity of the ridges, they are seen to be made up of elements that have consistent trends, which are inclined to the long axes of some of the ridges. One of the few exposures of bedrock in the region forms the hill near the southeast corner of figure 3. The ridges of sand are shown by the contours, and they are not related to the form of the hill, showing that they were not developed on the present surface.

"Arrowheads" or "wishbones" are a spectacular feature of the ridges. These vary in perfection from the simple type shown

in the region, one mile south of Villeroy (fig. 2), to the double type shown on the southwest corner of figure 2. It is noteworthy that in all cases the points of the arrowheads are directed southwest.

In addition to the pronounced features such as are shown on the topographic maps, there are low rounded ridges that at any one locality have two trends which intersect at about 80° . The low ridges are continuations of the higher ridges and may form the prolongations of parts of the arrowheads. The ridges, which are from one to 10 feet high and commonly from 25 to 50 feet wide, are not easily visible in the uncleared land, but on burned-over or cleared land, they may be seen to form a quadrille pattern on the surface. In general, the low ridges are continuous for considerable distances, and they are from 200 to 1000 feet apart, although they are apparently absent in some parts of the region. The trends of the ridges were measured at a number of localities, and statistical examination showed two maxima at $N 60^\circ E$ and $N 83^\circ E$.

The ridges and the surrounding plain are composed principally of sand in uniform beds from one to four inches thick.

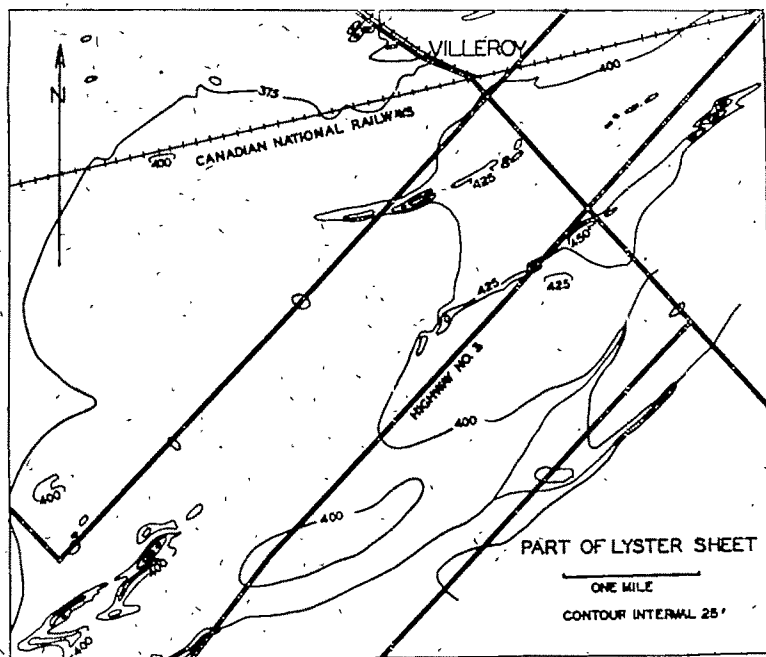


Fig. 2. Part of Lyster topographic sheet showing crevasse filling.

Little cross-bedding is seen. At some localities, fine well-bedded gravel is found.

A pit in one of the ridges, a mile southeast of Villeroy, has been exploited for sand. The uniform bedding on the flanks of the ridge dips 20° away from the axis of the ridge. On the axis of the ridge the bedding is somewhat irregular but tends to be horizontal. In this pit, the coarser gravel appears to occur at lower elevations near the axis of the ridge. Near the entrance to this pit, many fragments of shells broken by the passage of trucks occur. Whole shells were seen in sand near the top of the pit face. They are almost certainly in place for they do not have the scoured appearance of transported shells. The shells, identified for me by Dr. J. W. Laverdière, are *Macoma groenlandica*, *Saxicava rugosa*, and *Mya truncata*, all of which genera are common in the upper (Saxicava) clay and sand along the St. Lawrence valley in Quebec. These shells are certainly marine, and since they are in place, they show that marine water once covered this district.

ORIGIN OF THE RIDGES

At first sight, the higher ridges resemble eskers, as for example, the ridge two miles northeast of Laurier when it is viewed from the train or road. In detail, however, the ridges are unlike eskers in that they are less rounded in cross-section and less smoothly sinuous in plan. Tributaries to eskers are moderately common, but the arrowhead pattern seen on the ridges is not characteristic of eskers. Furthermore, it is a commonplace that the material of eskers is characterized by pronounced and rapid changes in size grades along the length,

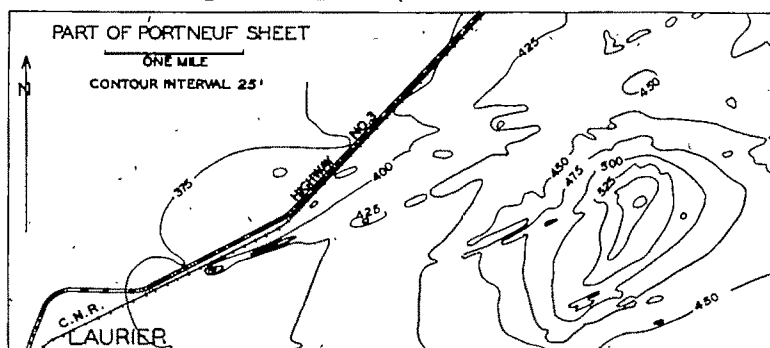


Fig. 3. Part of Portneuf topographic sheet. The hill on the southeast corner of the figure is bedrock. Note that the ridges extend across it.

whereas in these ridges, the material is uniform over considerable distances. Finally, marine shells are not commonly found in eskers.

Despite the fact that the ridges are not eskers, it is certain that ice had a role in their formation. Some material, now vanished, must have acted as retaining walls to protect and allow such ridges to form, and ice is the only substance that will fulfil the requirements. It is inferred that the ridges are in the direction of the channels, whose trends were in part determined by the direction of the crevasses. The arrowheads at the intersection of the ridges are thus the sites of enlarged crevasses, whereas the low ridges were the deposits formed in shallow channels on the ice surface. The larger and more irregular areas of elevated ground, for example $1\frac{3}{4}$ miles southeast of Villeroy, are probably the sites of depressions on the ice surface.

The even bedding of the sand and the marine fossils show that the sand was deposited from a sea that extended over the top of the ice sheet. Rock debris in or on the ice helped prevent it from being buoyant in the salt water.

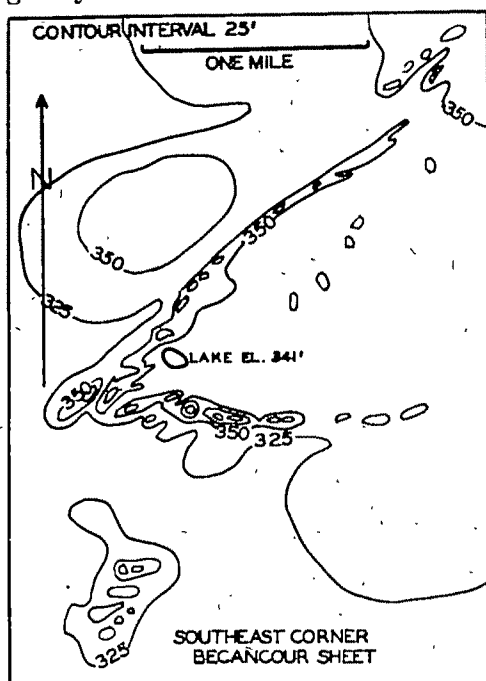


Fig. 4. Complex "arrowhead."

The fineness of the sediments composing the ridges and their exposed position above the plain after the ice melted would certainly allow such features to be obliterated in a few hours by wave movement in a large standing body of water, especially if the considerable fetch of the prevailing westerly winds at this place be considered. Chapman (1937, p. 117) suggests that single storms may have formed terraces in glacial lake Vermont. It is, therefore, probable that the surface of the sea was below the lowest ridge before the ice melted. Undoubtedly, the melting of the stagnant ice was retarded by the cover of glacial debris and marine sand.

The height of the present ridges gives the minimum thickness of the ice. The highest ridge stands 75 feet above the surrounding plain. Therefore, at this locality, there was at least 75 feet of ice. The upper limit of the marine submergence in this district determines the elevation of the surface of the sea in which the fossils lived. Goldthwait (1911, 1912) has determined the marine limit as 591 feet at a locality a mile south of Laurierville, only a few miles south of the features described here. Fossils at 425 feet elevation were the highest observed, and the thickness of ice sheet at this locality at the time sea crossed it was probably of the order of 170 feet. On the other hand, the lowest elevation at which ridges of this type are seen on the topographic maps is 800 feet, which is 290 feet below the marine limit. It is thus improbable that the ice on which the channels were developed was less than 75 feet and more than 800 feet thick as the sea advanced across it.

After much discussion, it has come to be agreed that eskers do not ordinarily form by the filling of channels on the top of ice. Their dissimilarities to certain types of crevasse fillings have been pointed out by Flint (1928). The principal argument against the superglacial origin of eskers is the common observation that streams on the surface of an ice sheet find, in a short distance, access to lower levels either at the bottom of or within the ice. Such an argument has no force in the case of ice submerged in water for the downward movement would be arrested by the pressure exerted by the surrounding water, which in the present case being saline, should be denser than fresh water. It is even possible that a reverse movement could occur, and the salt water would force fresh water upward through crevasses in ice. Such fresh water would be at the

temperature of melting ice and should not appreciably enlarge the crevasses.

The sequence of events in the formation of the ridges may be summarized as follows. An ice sheet became stagnant in this part of the valley of the St. Lawrence. Crevasses were etched as the surface was ablated. Superglacial streams that probably drained westward occupied some of the crevasses, and debris released during the ablation accumulated in the crevasses. When the surface of the ice had fallen to about 600 feet elevation, marine water flooded the region, and surface debris was reworked to give a cover of uniformly bedded sediments. The greatest thickness of sediments was in the crevasses and as the ice melted the sediments were let down. The slumping away from the thicker accumulation of sediments produced the present dips of 20° outward.

OCURRENCES OF FOSSILIFEROUS "ESKERS" AND CREVASSE
FILLINGS

In North America, a fossiliferous esker-like form has been described by Trefethen and Harris (1940) from near East Orrington, Maine. Abundant marine shells occur *in situ* in what is considered a crevasse filling. Nichols and Lord (1937) have reported shells in eskers near Weymouth, Massachusetts. They, however, believe that the shells are derived from older sediments for they say: "... apparently, as the glacier moved over the inter-glacial Boston Harbor, it picked up mud and sand which contained shells. Later, these shells were either incorporated with the till or were washed out of the ice and into the eskers and outwash deposits." The statement is interesting when it is considered that the till, particularly along the lower St. Lawrence (Dawson, 1898, p. 38) contains marine shells.

Professor Auguste Mailloux, of the Agricultural College at Ste. Anne de la Pocatière, found during the course of his work on soil classification in Quebec, an esker-like form with marine fossils. The locality is 1½ miles southeast of Ste. Philomène, which is 8 miles south of Ville La Salle, a suburb of Montreal. Examination of the Lachine topographic sheets shows that the region has a general elevation of 150 feet. A series of disconnected elongated ridges forms a line ten miles long trending S 20°W. In places, the summit of the ridge is at an elevation greater than 200 feet, and the higher parts of the ridge are

as much as a quarter mile wide. The map by Keele and Cole (1922) shows that the region is largely covered by till. Professor Mailloux states that 7 feet below the crest of the ridge, where it has been exploited for gravel, marine shells occur "by the shovelfull." No fossils were found in lower beds. Dr. Yves Desmarais (personal communication) states the ridge has considerable coarse gravel with cobbles.

The origin of the topographic features at such low elevation is not at once clear. The presence of marine shells in an esker at this position is remarkable, for it would have been mantled by the younger marine and freshwater deposits. The trend of the feature towards the mountain at Montreal suggests that it was formed by the meeting of currents in the sea or river, that it is a bar. Ridges with very coarse blocks near Hull, Quebec, have been considered the result of the interaction of sea and river-borne ice blocks in the declining stages of the sea by Chalmers (1898, p. 61), and Johnston (1917, p. 32) has accepted this explanation.

With the data at hand, the possibility that the Ste. Philomène ridge is the filling of the channel cut in stagnant ice cannot be ruled out. Stansfield (1915, p. 22), who examined the unconsolidated deposits at Montreal, suggested that clays and sands at the Glen, which is on the flank of Mount Royal near Westmount station, are ice contact deposits although he does not give his opinion on the position of the ice front at the time.

Crevasse fillings of sand have been described from the Cree Lake region, Saskatchewan, by Sproule (1939), who termed them "ice-crack moraines". The map and air photographs accompanying his paper show them as narrow ridges trending almost at right angles to drumlins and eskers around them and approximately parallel to a terminal moraine. An intersecting pattern of crevasses is preserved in the ridges, and obtuse angle of intersection is bisected by the direction of ice retreat and advance. Not enough data are available to know whether the same is true in Lotbinière.

Sproule emphasizes the sharpness of the features and insists on the absence of a standing body of water. Mawdsley (1936) considered that the washboard moraines of the Chibougamau district, Quebec, formed in the crevasses in an ice sheet near a standing body of fresh water. Norman (1938) showed that the washboard moraines are terminal features. Shaw (1944) de-

scribed similar features formed against marine water east of James Bay. None of the papers on washboard moraines mentions the filling of crevasses by fine-grained sediments with a standing body of water advancing across the ice.

The many references to eskers as compared with the few descriptions of crevasse fillings suggests that eskers are developed principally in or below ice and that special conditions are necessary for at least the preservation of crevasse fillings of fine material.

EXTENT OF LOTBINIERE ICE

In order to determine the extent of the former stagnant ice, a careful examination of the topographic maps was made. It failed to show any similar ridges below 300 feet elevation. It is possible, although the ice was loaded with debris, that where thicker, it became buoyant in the sea and calved into the estuary. Currents carried the icebergs out to sea.

The central part of the Aston topographic sheet shows irregularly disposed ridges and knolls that suggest kames. These features were not examined on the ground. They occur near elevation 300 feet and were possibly formed where the ice front was embayed. The narrowness of the bay would probably prevent the terraces forming there, for the best-developed terraces on the north side of the St. Lawrence River show evidence of strong current action.

T. H. Clark, in an unpublished report in the files of the Quebec Department of Mines, has described an esker near Grand St. Esprit, in the northwestern part of the Aston topographic sheet, 20 miles west of the nearest crevasse-fillings. He comments that it is the only esker he has observed on the lowlands. Examination of the map shows that the general surface in the district is at altitude 200 feet. The esker, which trends N 20°W, has a typical sinuous pattern. Clark states that the esker is composed of sand and gravel. In view of the exposed position, it is unlikely that the sand would survive in standing water for long, hence the esker was probably formed after the decline of the sea.

Even more telling evidence for the presence of a protecting mantle of ice on the south side of the St. Lawrence is the absence of terraces such as are found on the north side of the river. According to Goldthwait (1932), the 210-foot terrace

which marks a halt point in the lowering sea level, is of common occurrence on the north side of the St. Lawrence: nevertheless, no traces of a terrace at this elevation is seen on the south shore between Lac St. Pierre and Québec. This in itself shows that at least some ice persisted until sea level had fallen to 210 feet, although the ice front may have been locally embayed, but the bays were not so wide as to allow currents to cut terraces. Most of the terraces on the north side of the river show evidence for current trimming. On the other hand, there are many occurrences of an 105-foot terrace on both sides of the river showing that the sea reached the surface of the rock or the till by the time that the surface had fallen to this level.

Northwest of the region with the crevasse fillings, much of the valley of the St. Lawrence is below 105 feet elevation, and hence it is difficult to determine whether the ice sheet ever extended there; however, as will be described in ensuing paragraphs, there is evidence that an ice sheet once rested against a considerable length of the Laurentian escarpment along the north side of the St. Lawrence lowlands.

The best evidence comes from the region where the Batiscan and St. Maurice rivers cross the boundary between the lowlands and the Laurentian region (fig. 1). In this section, the Laurentian escarpment is much lower than is commonly the case, and a triangular area with a base 25 miles east-west and its surface near 400 feet altitude forms an embayment extending about 15 miles into the Laurentian uplands. Part of the southern limit of the embayment is marked by a narrow ridge that stands as much as 75 feet above the ground to the north and extends 5 miles east and west of the village of St. Narcisse, which is near Batiscan River. The ridge is made of coarse gravel with large blocks and shows a cross-bedding that dips steeply northeast, that is, toward the Laurentian region. On the northwest side of the ridge, there is a gradation in a short distance from boulders through cobbles to sand and silt going northwest. The ridge shows so many features in common with the Newington moraine described by Katz and Keith (1918), that there is no doubt that it is also a moraine and was formed when ice stood along the base of the embayment.

Another ridge, Mont Carmel, also on the base of the triangular area of the embayment reaches 620 feet elevation at a local-

ity 6 miles west of the moraine. This ridge, which is about 6 miles long, is composed entirely of gravel and sand which are cross-bedded with steep dips northwest. It is considered to be a delta formed with ice on the south and open water on the north. Another and lower delta of similar character is anchored on the Laurentian escarpment at Charette, which is 12 miles west of the delta just described.

The deltas and moraines provide evidence that the ice once extended along a considerable part of the edge of the Laurentian region, and it is probable that the whole area of the St. Lawrence lowlands in this region was occupied by ice when the Laurentian upland to the north was free from it. It is only reasonable to consider that the moraine and deltas mark the limit of the same ice sheet that stagnated in Lotbinière.

The deltas and the moraine were terraced by the declining sea and this, with the evidence of stagnant ice on the south side of the St. Lawrence, suggests that the sea gained entry to the lowlands along their northern edge.

SOURCE OF THE ICE SHEET

The silts on the northwest side of the moraine near St. Narcisse and the gravels of the delta deposits lie upon massive clays of the Leda type, and in view of the fact that Leda clays are commonly considered deposits of the Champlain sea formed soon after the Laurentide ice retreated across the estuary of the St. Lawrence, the question of the age and source of the Lotbinière ice sheet is raised. Furthermore, the Lotbinière ice is older than the gravels, sands and silts with clay that have been called Saxicava sand. One, therefore, is faced with the problem of an ice sheet present between two marine formations.

Many observers of the superficial deposits in eastern Canada have recorded the presence of two tills or of till overlying marine clay. Most of the references have been collected by Coleman (1927, 1932, 1941), who concluded that Leda clay is interglacial, and that the Saxicava sands, silts and clays are post-glacial. Disregarding the assignment of the Leda clay to an interglacial period, Coleman's conclusion that two marine formations are present and unconformable is probably valid. Such a view was long ago expressed by Dawson (1893.)

The Lotbinière ice then was not simply a relic of the retreating Laurentide ice sheet, that was crossed by the incoming

Champlain sea. The fact that the boulders and 'pebbles' in Lotbinière and in the moraine and delta deposits are from a Laurentian source would support such a contention, but the relationship to the Leda clay invalidates it as does also the fact that there was open water on the lower parts of the Laurentian region, north of the deltas and the St. Narcisse moraine.

The possibility of an ice sheet from the Appalachian region must be considered. Chalmers (1898), who inferred the presence of ice caps in the Appalachian region near Quebec, believed a piedmont glacier formed in the St. Lawrence valley. Clark (1937) and Cooke (1937) have published evidence of the flow of ice northward from the Appalachian region to the St. Lawrence lowlands. However, other workers in the district, notably MacKay, who records striae with two trends in the Beauceville district, believe that the ice in the Appalachian region was part of the Laurentide sheet. MacKay (1921) concluded from striae that the ice moved S 15°E and S 65°E, but he was unable to determine certainly which set of striae is older.

One piece of evidence in the direction of ice retreat and relative age of the striae is described, but not discussed by MacKay (1921, p. 37). Along the Chaudière River in the Beauceville region at a locality where striae of both sets occur, an esker, which trends S 10°E and is 3 miles long, begins at elevation 900 feet on the north and reaches 540 feet on the south end. Although the evidence is not conclusive, the known habit of eskers suggests that the ice was retreating northward. The esker probably belongs to the latest ice sheet in this place, and therefore, the S 15°E striae are probably the younger set. And the direction is the same as that of striae in the Laurentian region.

Chalmers (1898) inferred that the ice cap in the Appalachian region was in existence before the Laurentide ice advanced into the region. The Lotbinière ice was, however, younger than the Laurentide ice and hence could not belong to an ice cap developed on the Appalachian highlands if Chalmers' inferences regarding the age are correct. The principal objection to an Appalachian source of the ice is the presence of the erratics of Laurentian rocks. It is difficult to conceive how the ice transport of Appalachian rocks by an ice sheet originating in the Appalachians could be avoided. The suggestion that the erratics could have been picked up from an older Lauren-

tide till is not helpful for the Lotbinière ice sheet probably advanced across Leda clay. The Leda clay is believed to be thick although few good sections of the Leda clay and Saxicava sand have been measured; however, one measured by Clark (1947) on a landslip scar near St. Esprit, which is 9 miles west of the nearest crevasse filling, is instructive. It is shown as table 1, and is unusual in the presence of *Leda* shells at a locality so close to Quebec. The base of the section is at elevation

TABLE 1.

		Ft.	In.	
A	Soil and sand ? non-marine	2	0	Top of cliff.
		2	0	Unbanded sand and soil. Banded brown sand.
B	Saxicava sand	13	4	Finely banded clay at top, grading downwards into very fine sandy clay, becoming more sandy towards the base.
		6	9	Poorly stratified sand. Fossils abundant, mostly <i>Saxicava</i> . Most of the fossils in slumped material below came from this layer.
			4	Well-bedded, sand with abundant fossils, mostly <i>Saxicava</i> .
			11	Unbanded sand, no fossils, but with boulders up to 6" across.
			7	Blue clay, no fossils.
		1	6	Sand, unbanded, no fossils.
C	Leda clay	25	10	Well-banded unctuous clay in layers 1 to 2" thick with sandy partings. Gray on outer surface, black and fetid $\frac{1}{4}$ " or more within. <i>Leda glacialis</i> , with epidermis, occurs abundantly about 8' 6" below the top.
D	Algal and hydroid clay	39	1	Clay in 6" beds separated by rusty sand partings up to 1" thick. Black and fetid within. The lower 20' contain algae and hydroids, but practically no other fossils.
E	Mya clay	2	0	Blue clay, well bedded, with fairly abundant marine fossils, including <i>Mya truncata</i> . Water level, August, 1945.
		94	4	Total thickness of section.

100 feet. It is significant that no certain till occurs between divisions "C" and "B" of the section, although it is possible that the lower 3 feet of "B" is a modified till, or perhaps this region is the site of embayment in the ice front, such as was suggested for the central part of the Aston sheet, and the till was removed. It is to be noted that the 67 feet of clay in the three lower divisions of the table would be called Leda clay. The break between Leda clay and Saxicava sand is characteristic of the region along the valley of the St. Lawrence, although at many localities boulders are larger and more numerous than in Clark's section. The break probably corresponds in time to the emergent period at Ottawa (Johnston, 1916, 1917; Antevs, 1939.)

The foregoing considerations would rule out both an Appalachian and the main Laurentide ice sheets as the source of the Lotbinière ice. However, the presence of the erratics from the Laurentian region indicates that the ice came from there. Chalmers (1898) and others have plotted glacial striae that are directed upriver in the Laurentian north of Quebec. The striae trend away from the large and high monadnock that lies in *Parc des Laurentides* between Quebec and Lake St. John and are younger than the Laurentide striae. It is inferred that, after the retreat of the Laurentide ice sheet and deposition of the Leda clay, a local ice cap developed on the monadnock, and a tongue of ice from it occupied the northeastern part of the St. Lawrence lowlands before marine water broke in for a second time. The evidence in support of this conclusion will be given in another paper.

CONCLUSION

The ridges of Lotbinière are somewhat modified casts of the channels in stagnant ice that existed when marine water advanced into the region in late Pleistocene time. The ice sheet once occupied the entire width of the St. Lawrence valley and was probably from a Laurentian source which was a local ice cap. Although the best evidence of the former extent of the stagnant ice is given by the crevasse fillings, other features shown on the topographic maps show that the surface was protected by ice until the sea fell below 210 feet but was exposed to wave action by the time the surface was at 105 feet.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance received from my colleagues at Université Laval: members of the Department of Geology discussed the problems not only in the field but also in course of the writing of the paper.

Dr. R. F. Flint, of Yale University, has kindly read the paper and offered many valuable suggestions.

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Maps—Canada, National Topographic Series, Scale: 1" = 1 mile. The letters refer to figure 1.

Aston (A) 1920 revised 1944; Bécancour (B), 1921 reprinted 1938; Chaudière (C) 1916 revised 1944; Grondines (G), 1931; Lyster (L) 1922 revised 1944; Portneuf (P) 1920 revised 1944; Quebec (Q) 1914 revised 1944; Shawinigan (S) 1928 reprinted 1949; Three Rivers (T) 1921 revised 1944; Yamaska (Y) 1922 revised 1937.

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THE *IRVINGELLA MAJOR* ("PTYCHOPLEURITES") FAUNIZONE OF THE UPPER CAMBRIAN

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ABSTRACT. The fauna of the "*Ptychopleurites* zone" is reviewed and a new genus erected for the trilobite *Ptychopleurites amplexolucata* Frederickson. The geographic and vertical position of this assemblage in the standard faunal sequence of the North American Upper Cambrian is discussed. It is proposed that the name of the time-stratigraphic unit characterized by this fauna be changed from *Ptychopleurites* zone to *Irvingella major* faunizone.

FAUNAL ZONE TERMINOLOGY

THE writers adopt the faunal zone terminology discussed by Arkell in 1933 and by Moore in 1945 (pp. 312-315). The term faunizone is employed to designate strata deposited during the life span of an assemblage of organisms. Strata deposited during the life span of a particular genus or species form a biozone. An epibole includes beds formed only during the time of greatest abundance of a particular species or genus.

The faunal zones set up as a standard for the North American Cambrian sequence (Howell *et al.*, 1944, p. 994) comprise trilobite faunizones of two orders of importance: (1) strata containing vertically well-delineated assemblages of genera, *e.g.* the *Elvinia* zone; (2) strata characterized by the association of only two or three genera any of which may range vertically outside the limits of the zone, *e.g.* the *Platystrophia* or *Saukiella* "zones."

The Cambrian correlation chart extends the names of certain faunizones beyond the geographical limits of occurrence of the characteristic fossil whose name the zone bears, if one or more other genera are common to the strata of the type area and the area under consideration. This is a relatively sound procedure when the faunas are well-delineated assemblages of the first order (such as the *Cedaria*, *Crepicephalus*, *Aphelaspis*, *Elvinia* and *Conaspis* faunas) but may lead to incorrect correlation when using small, poorly delineated associations (faunizones of the second order). For example, the Trempealeauian "zones" of the standard Croixan section are not discernible in collections made by Wilson from the Conococheague limestone of the central Appalachians, the key gen-

era of these small assemblages being mainly absent and only certain long ranging forms quite common.

It is possible that the attempt to make certain of these Cambrian faunal zones continent-wide in extent is partially obscuring important facts of faunal migration and facies or geographical control of trilobite faunas. Some detailed work already definitely indicates this possibility. Lochman (1948, p. 452) has indicated the facies equivalence in time of the Middle Cambrian *Albertella* and *Kochaspis liliana* zones and the *Zacanthoides-Anoria* and *Glossopleura-Kootenia* zones. Bridge (1937, p. 236) has suggested that possible facies equivalents of the *Dikelocephalus* zones exist outside of the Croixan siltstone lithology. It also seems probable that the large faunal assemblage of the *Elvinia* zone of the standard section is almost completely replaced in the eastern part of the central Appalachian trough by another group of trilobite genera thus far undescribed.

Considering the above facts the writers believe that Cambrian biostratigraphy is reaching a point of such refinement that zonal terminology as used within a province as large as North America should always connote the possibility of areal restriction. We emphasize the geographic significance of a faunizone. The unit should be extended only so far as its characteristic assemblage occurs. Further, this assemblage should possess regional geographical continuity. Minor facies faunas (e.g. reef inhabitants) might be expected to occur locally within its province, and tend to obscure the regional picture. These should be excluded from the faunizone.

Though controlled vertically and geographically by ecologic factors, the widespread distribution and short vertical range of most Upper Cambrian faunizones make them all-important units for purposes of correlation. Essentially their use in Cambrian biostratigraphy of North America has been, in practice, that of time-stratigraphic units.

DEFINITION AND PAST USAGE

The term "*Ptychopleurites* zone" has been used by Cambrian paleontologists in recent years to identify a few feet of strata characterized by a small assemblage of trilobite genera. The strata lie within the Franconian stage of North America; beds below them possess an *Elvinia* fauna and those above a *Conaspis*

fauna. Although the assemblage includes a species assigned in the past to *Ptychopleurites* Kobayashi 1936, it is better characterized by numerous trilobites belonging to species of *Irvingella*. The assemblage was originally recognized by Twenhofel, Raasch, and Thwaites (1935, pp. 1703-1704) in shaly micaceous sandstone of the Franconia formation. It was termed the *Irvingella major* fauna and described as including several species of brachiopods and three undescribed trilobite genera.

Raasch (1939, pp. 91, 92, 115) describes the fauna as the *Ptychopleura* or uppermost subdivision of the "*Camaraspis* zone." (The Wisconsin *Camaraspis* fauna is synonymous with the *Elvinia* fauna of present usage. *Ptychopleura*, Kobayashi's original name, was a synonym and was replaced with *Ptychopleurites* by Kobayashi in 1936.)

Dorf and Lochman (1940, pp. 545, 547) recognized the "*Irvingella major* zone" in the columnar limestone of the Snowy Range formation in southern Montana. Howell *et al.* (1944) in the Cambrian correlation chart list the genera *Ptychopleurites*, *Irvingella*, *Berkeia*, and *Deadwoodia* as constituents of the "*Ptychopleurites* zone" and indicate its development in numerous sections of the Rocky Mountains and mid-continent areas of North America. Lochman and Duncan (1944, pp. 2, 13) use "*Ptychopleurites* zone" in the same sense, stating that it is always present in the columnar limestone lithology of the Snowy Range formation of Montana.

Wilson in 1948 added the genus *Sulcocephalus* to the faunal assemblage and in 1949 (p. 30) lists this form with "*Ptychopleurites*" and *Irvingella* from the middle Morgan Creek member of the Wilberns limestone of Texas as constituents of his "*Irvingella* subzone of the *Elvinia* zone."

Frederickson (1948, p. 803) described the new species *Ptychopleurites amplexulata* and in 1949 (p. 356) added the genus *Kiowaia* to the "*Ptychopleurites* zone." Neither Frederickson nor Wilson found the genera *Berkeia* and *Deadwoodia* in the numerous exposures of this horizon in Oklahoma and Texas although these are listed by Howell *et al.* (1944, p. 994) as characteristics of the zone.

The present paper furnishes current information on genera of the *Irvingella major* fauna and discusses the unit as a time-stratigraphic division of the Upper Cambrian sequence (table 1).

TABLE 1

Relation of the *Irvingella major* faunizone to the *Elvinia* and *Conaspis* faunizones. The linear sequence of x's mark the range or biozone of a genus. The large X's represent the epiboles of the long ranging genera *Irvingella* and *Eoorthis*. Where the biozone and epibole correspond, small x's are used.

<i>Elvinia</i> faunizone	<i>Irvingella major</i> faunizone	<i>Conaspis</i> faunizone
<i>Irvingella</i>	<i>Irvingella</i> biozone	
	<i>Irvingella</i> epibole	
<i>Elvinia</i> biozone	<i>Comanchia</i> biozone	
	<i>Sulcocephalus</i> biozone	
<i>Berketa</i> biozone	<i>Kiowata</i> biozone	
<i>Deudwoodia</i> biozone		<i>Eoorthis</i> epibole
	<i>Eoorthis</i> s. l. biozone	
		<i>Orygmaspis</i> biozone

The genus *Ptychopleurites* Kobayashi 1936.—Dr. W. A. Bell of the National Museum of Canada, Ottawa, Ontario, kindly furnished the writers with plaster casts of Kobayashi's original material upon which *Ptychopleurites brevifrons*, the genotype, was founded. These show that Kobayashi's illustrations of the species have been retouched to some extent. The material upon which the genus is founded is extremely poor. The holotype lacks palpebral lobes, the posterior limbs are incomplete and the paratype cannot be matched certainly with its illustration (Kobayashi, 1936, plate 21, fig. 8). The specimens were collected from a locality on the Alaskan-Yukon boundary in a section of dubious position in the Upper Cambrian faunal sequence. Kobayashi considered the genus to be as young as the *Briscoia* fauna and lists the new species *Parabolinella ? punctolineata* and *Agnostus subosesus* as associates. The genus *Parabolinella* may range from middle Franconian to high Trempealeauian (Lake 1906-1946, p. 63 reports *Parabolinella* with *Dikelocephalus* in Upper Lingula flags) but has never been found as low as the *Elvinia* fauna. Kobayashi's agnostid species is stated to belong unquestionably to the *Agnostus pisiformis* var. *obesus* group. Westergaard (1947, p. 4) states that this form ranges through most of the *Olenus* zone. This Atlantic province zone is generally considered middle Franconian in age (Howell and Lochman, 1939, p. 116). Thus while Kobayashi's fauna may be as old as the *Conaspis* assemblage of North America, it also may be considerably younger. In either case, this fauna is definitely younger than the *Irvingella major* fauna.

The inclusion of *Ptychopleurites* in the *Irvingella major* fauna was based upon the generic assignment of what is now known as *Ptychopleurites amplooculatus* Frederickson. A comparison of actual specimens of this Franconian species with the genotype casts indicates some similarities but also differences which may be considered of generic importance (see discussion of *Comanchia* below).

DISCUSSION OF GENERA OF THE IRVINGELLA MAJOR FAUNA

As now constituted the *Irvingella major* fauna in the mid-continent region includes only the associated genera *Irvingella*, *Sulcocephalus*, *Kiowaia* and *Comanchia* (erected here for *Ptychopleurites amplooculatus* Frederickson).

Irvingella Walcott 1924 is by far the most common genus in the fauna and thus gives its name to the bio-stratigraphic unit characterized by this fauna. Although Resser described numerous species of *Irvingella* (1942, pp. 18-25), the writers consider most of these to be synonyms of *Irvingella major* based in large part on growth stages. The genus first appears with the typical *Elvinia* fauna but is much more common above it in association with *Comanchia*. It has been stated by Twenhofel *et al.* (1935, p. 1704), by Raasch (1939, p. 95), and by Howell *et al.* (1944, p. 994) that the genus *Irvingella* recurs above the *Ptychaspis-Prosaukia* fauna of the Croixan area, but in the writers' experience this is not so; probably species of *Chariocephalus* or *Drumaspis* have been mistaken for those of *Irvingella*. In the U. S. National Museum collections in Washington, D. C. a slab is present from the Croixan region which contains *Irvingella* and certain conaspid species showing that unless specimens of the former genus have been reworked from the Ironton member, it may range up into the basal *Conaspis* fauna.

Sulcocephalus Wilson 1948. This genus is a persistent member of the assemblage. *S. candidus* (Resser) is known in the *Irvingella* coquina with *Comanchia* from six sections in the Llano Uplift of Texas (Baldy Mountain, Backbone Ridge, Threadgill Creek, Marble Falls-Burnet highway, Camp San Saba, and Sponge Mountain-Cold Creek (U.S.N.M. loc. 14b)). *Sulcocephalus benesulcatus* Wilson is known only from the Threadgill Creek section in a collection made by Dr. Virgil Barnes of the Texas Bureau of Economic Geology. It is as-

Explanation of Plate 1

Figs. 1-3. *Sulcocephalus sculptilis* (Resser). Holotype, dorsal, anterior and profile views of cranium, X4, Honey Creek formation, Arbuckle Mts., Oklahoma. Photographs furnished by Dr. G. A. Cooper of the U. S. National Museum.

Figs. 4-5. *Sulcocephalus candidus* (Resser). Hypotype, dorsal and profile views of cranium, X8, Morgan Creek member, Wilberns limestone, Baldy Mt., Llano Uplift, Texas.

Figs. 6-7. *Comanchia amplooculata* (Frederickson). Holotype, dorsal and profile views of cranium, X10, Honey Creek formation, Oklahoma.

Figs. 8-9. *Ptychopleurites brevifrons* (Kobayashi). Plastotype, dorsal and profile views of plaster cast of Kobayashi's holotype specimen, X10.

Fig. 10. *Ptychopleurites brevifrons* (Kobayashi). Reproduction of Kobayashi's original illustration of the holotype of *P. brevifrons*, X10 (2½ x original illustration).



1



2



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3



5



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8



10

sociated with *Eoorthis* and *Irvingella* in a bed of glauconitic limestone. The Honey Creek limestone of Oklahoma has yielded a species of *Sulcocephalus*, originally described as "*Berkeia*" *sculptilis* by Resser in 1942 (p. 93, plate 16, figs. 1-4), but herein assigned to the genus *Sulcocephalus*. The genus is also present in the collections from Wisconsin in the Milwaukee Public Museum (M.P.M. no. 976) from 6 miles south of Grand Marsh, Wisconsin. It is associated with cranidia and pygidia of *Irvingella* and with *Comanchia*. *Sulcocephalus* is quite similar to the genus *Berkeia*, differing from this genus of the *Elvinia* fauna in possession of narrower fixed cheeks and a central posterior extension of the border. Quite probably this occasions the reference of *Berkeia* to the *Irvingella* major fauna in the Cambrian correlation chart (Howell *et al.*, 1944).

Kiowaia Frederickson 1949 (p. 356). *Kiowaia timberensis* Frederickson; from the Honey Creek limestone of Oklahoma, is the only published species of this genus, but Gilbert O. Raasch (personal communication, dated December 9, 1949) has indicated its possible occurrence in the *Irvingella* major fauna of Wisconsin.

Comanchia Frederickson, n. gen. This monotypic genus was erected to include the species *Ptychopleurites amplexulata* Frederickson. This species has been described from the *Irvingella* major horizon in Texas and Oklahoma and has been reported as being present in the zone in Wisconsin (Raasch, 1939, p. 91). The genus as now known is confined to the *Irvingella* major faunizone.

GEOGRAPHIC DISTRIBUTION OF THE IRVINGELLA MAJOR FAUNIZONE

This assemblage is commonly found in the middle of the Morgan Creek limestone member of the Wilberns formation of the Llano Uplift in Texas and in the middle of the Honey Creek limestone of the Arbuckle and Wichita mountains of Oklahoma. Detailed information about local occurrences of the fauna in the southwest may be obtained from papers by the writers (1948 and 1949).

Dr. Gilbert O. Raasch of the Illinois Geological Survey has kindly furnished the writers with details of the areal distribution of the fauna in the Croixan region:

" . . . the fauna occurs only in a rather restricted area in central Wisconsin, including the counties of Adams, Juneau,

and northeastern Sauk. The faunal unit thins westward until it is less than an inch thick at a locality three miles north of Reedsburg, Sauk County. It has thinned to disappearance by the time the Goodenough Hill is reached, but specimens have been found in residual float on the high mound west of Point Bluff, north of Mauston, Juneau County.

"North of the Baraboo ranges in Sauk County, the zone seems to be continuous but only a few feet thick in Dellona Township (Section 10, 11, 23, 26) and in the northeast corner of Reedsburg Township (Sec. 1). It is not present by the time the city of Reedsburg is reached.

"In Adams County, east of the Wisconsin River, the unit thickens to exceed six feet in thickness at the shalepit in SE $\frac{1}{4}$ of NW $\frac{1}{4}$. Section 11, T 17N, R 7 E, near Pilot Knob, Adams County. Other localities in Adams County are Section 25; NE $\frac{1}{4}$ of Section 11; SE $\frac{1}{4}$ of Section 2, all in T 12 N, R 6 E; SE $\frac{1}{4}$ of Section 25, T 16 N, R 6 E; and Friendship Mound at Adams Station."

According to Twenhofel, Raasch, and Thwaites (1935, p. 1699) the *Irvingella major* faunal assemblage occurs in fine-grained, micaceous sandstone and siltstones which, "overlie the Iron-ton with its typical fauna and lithology. The fossils indicate a closer relationship to the Iron-ton than to the overlying Goodenough, but the lithology is that of the basal Goodenough."

In general the *Irvingella major* faunizone is typically present in the Franconian stage of the mid-continent region. Collections from the Davis formation of Missouri do not show it, but no detailed stratigraphic paleontology has yet been done in the Upper Cambrian of this area.

Genera of the *Irvingella major* faunizone in the Rocky Mountain Cambrian sections are reported by Lochman and Duncan (1944, pp. 2, 3, 18) as always associated with the columnar limestone of the Snowy Range formation. However, numerous trilobites of the *Elvinia* fauna including *Kyphocephalus*, *Deadwoodia*, *Burnetia*, *Cheilocephalus*, and *Dellea*? were collected by Wilson from the columnar limestone in four sections of the Snowy Range formation of southern Montana and northern Wyoming (Mill Creek, Grove Creek, Shoshone Canyon, and Boysen in Wind River Canyon). No genera of the *Irvingella major* faunizone were found except *Irvingella* which

occurs through a thickness of 10 feet of strata above the *Collenia major* reefs (columnar limestone). Miller (1936, p. 81) states that *Irvingella* occurs about 15 feet above the *Elvinia* fauna in the Wind River and Teton Mountains. It may be that the faunizone is represented immediately above the columnar limestone but as yet there is no positive evidence that the typical mid-continent assemblage of genera is present in the Rocky Mountains.

A study by Wilson on Franconian strata of the Central Appalachians failed to discover the *Irvingella major* faunizone. In the western Appalachian geosyncline of central Pennsylvania, the Ore Hill member of the Gatesburg formation generally contains about 40 feet of unfossiliferous dolomite in the stratigraphic position of the *Irvingella major* faunizone between the typical *Elvinia* fauna in the basal strata and the *Conaspis* fauna in the upper beds. None of the genera of the *Irvingella major* assemblage were found in the Ore Hill except *Irvingella* which was present in the underlying *Elvinia* fauna.

Considering the facts now at hand, therefore, it seems best to restrict the *Irvingella major* faunizone to the mid-continent region.

Vertical relations of the faunizone.—The wide geographic distribution of the *Irvingella major* faunizone in the mid-continent area is remarkable in view of its extreme thinness. In Oklahoma and Texas where it has been best studied to date, it occurs in less than 5 feet of beds. Thicknesses in the Croixan region have already been noted; the unit in central Wisconsin varies from 6 feet to a few inches in a westerly direction.

It is believed that over the mid-continent area the biozones of *Comanchia*, *Sulcocephalus*, and probably also *Kiowaia* always fall between the stratigraphic ranges of the *Elvinia* and *Conaspis* trilobite faunas. The biozones of these genera coincide with the epibole of *Irvingella*.

Though in the writers' experience no proof exists of the mixing of trilobite faunas of the *Irvingella major* and *Conaspis* faunizones, Raasch (1939, p. 94 and in a personal communication) implies that such occurs through a few inches of beds in some Croixan sections. There is no evidence of mixing of the *Irvingella major* and *Elvinia* faunas with the exception of *Irvingella*. These statements do not apply, however, to the brachiopod genera *Eoorthis* and *Billingsella* which span the

boundary between the faunizones discussed above, reaching their acme with the *Conaspis* fauna. In Wilson (1949, pp. 27-28) faunal lists containing misidentifications of two trilobites indicate a mixing of *Irvingella major* and *Elvinia* zone faunas which recollecting and inch-by-inch remeasurement of the Baldy Mountain, Backbone Ridge, Morgan Creek, and Camp San Saba sections of Texas have failed to substantiate.

The *Irvingella major* fauna shows a closer relation to the underlying *Elvinia* assemblage than to the overlying conaspid trilobites. This fact was recognized by Twenhofel, Raasch, and Thwaites (1935, pp. 1703-1704). Not only does the genus *Irvingella*, a typical member of the *Elvinia* fauna, reach its zenith in the beds containing the higher assemblage, but there is also a close relation between the older genus *Berkeia* and its possible descendant *Sulcocephalus*. Undescribed material from the Ore Hill limestone member of the Gatesburg formation in Pennsylvania indicates even closer kinship than does a comparison of the genotypes.

Genus *Comanchia* Frederickson, n. gen.

Cranidium with elongate appearance because of narrow posterior limbs. Glabella convex, quadrate, rounded anteriorly; three pairs of weak, oblique glabellar furrows; occipital furrow straight across center, bent forward and more deeply impressed at sides. Brim narrow, flat; border flatly convex, tapering slightly laterally, more than twice width of brim. Fixed cheeks narrow but expanded at palpebral lobes which are elevated and elongate, extending from position between first and second pair of glabellar furrows almost to occipital furrow; width of palpebral lobes equal to one-third glabellar width at midpoint; wide convex palpebral band separated from inner cheek by narrow furrow; faint ocular ridges present. Posterior limbs narrow, elongate, strap-like with narrow, deep marginal furrows. Free cheek not known.

Facial suture cutting anterior margin at center, curving out around border, then converging to palpebral lobe around which it curves gently; thence sharply outward at nearly right angles to axial line and around posterior limb to posterior margin.

Average cranidium very small, $3\frac{1}{2}$ mm. long, 5 mm. wide across posterior limbs. Surface of test minutely granular.

Genotype: Comanchia amplooculata (Frederickson).

Remarks.—The genotype was originally assigned to the genus *Ptychopleurites* Kobayashi (Frederickson, 1948, p. 803), but at that time attention was called to the wider posterior limbs and small palpebral lobes of Kobayashi's genotype. However, an examination of a plaster cast of Kobayashi's original specimens shows that the palpebral lobes are not preserved at all, and that the posterior limbs are very poorly preserved, but apparently even wider than Kobayashi figured them.

Certain general similarities in the cranidium are apparent in comparing the two genera but the following generic differences exist:

1. Judging from the width of the posterior limbs, the palpebral lobes are apparently smaller and differently shaped in *Ptychopleurites* than in *Comanchia*.

2. The glabella of *Ptychopleurites* is much more convex, the dorsal furrow more deeply impressed, and the occipital lobe is narrower and more convex.

3. The posterior limb of *Ptychopleurites*, though poorly preserved, indicates a triangular shape, quite different than the strap-like limbs of *Comanchia*.

4. The border is narrower, very convex, and much more depressed laterally in *Ptychopleurites*.

Comanchia amplooculata (Frederickson)

Plate 1, figures 6, 7

Ptychopleurites amplooculatus Frederickson 1948, Jour Paleontology, vol. 22, p. 803, plate 123, figs. 9-11.

Ptychopleurites amplooculata Frederickson, Wilson, 1949, Jour. Paleontology, vol. 23, p. 42, plate 10, fig. 4, plate 11, figs. 8, 9.

Remarks.—Both of the above descriptions are extensive and include several photographs of specimens of the species from Texas and Oklahoma.

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